Defense Threat Reduction Agency
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TECHNICAL REPORT

Radiation Doses to Skin From Dermal Contamination

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A. Iulian Apostoaei and
David C. Kocher

Prepared by:
SENES Oak Ridge, Inc.
Center for Risk Analysis
Oak Ridge, Tennessee

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14. ABSTRACT
This report presents a methodology for estimating radiation doses to skin from dermal contamination due to a uniform deposition of airborne radioactive material in specific regions of the body. This methodology includes a model to estimate increases in doses due to long-term retention of radioactive material on skin when removal by showering is incomplete. The primary focus of this report is estimation of doses from exposure to electrons (beta particles) emitted by radionuclides on the body surface. Estimation of doses from radionuclides that emit alpha particles also is considered. Models to estimate doses to skin from dermal contamination in various scenarios are described, including exposure to descending fallout from a nuclear weapon detonation and exposure to material resuspended from the ground surface by different human activities or the wind.

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CONVERSION TABLE

Conversion Factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY → BY → TO GET
TO GET ← BY ← DIVIDE

angstrom	1.000 000 x E -10	meters (m)
atmosphere (normal)	1.013 250 x E +2	kilo pascal (kPa)
bar	1.000 000 x E +2	kilo pascal (kPa)
barn	1.000 000 x E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 x E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 x E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 x E +1	*giga becquerel (GBq)
degree (angle)	1.745 329 x E -2	radian (rad)
degree Fahrenheit	$t_k = (t^o f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 190 x E -19	joule (J)
erg	1.000 000 x E -7	joule (J)
erg/second	1.000 000 x E -7	watt (W)
foot	3.048 000 x E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 x E -3	meter^3 (m^3)
inch	2.540 000 x E -2	meter (m)
jerk	1.000 000 x E +9	joule (J)
joule/kilogram (J/kg) radiation absorbed dose	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 x E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 x E +3	kilo pascal (kPa)
ktap	1.000 000 x E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 x E -6	meter (m)
mil	2.540 000 x E -5	meter (m)
mile (international)	1.609 344 x E +3	meter (m)
ounce	2.834 952 x E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 x E -1	newton-meter (N-m)
pound-force/inch	1.751 268 x E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 x E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 x E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 x E -2	kilogram-meter^2 (kg-m^2)
pound-mass/foot^3	1.601 846 x E +1	kilogram-meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 x E -2	**Gray (Gy)
roentgen	2.579 760 x E -4	coulomb/kilogram (C/kg)
shake	1.000 000 x E -8	second (s)
slug	1.459 390 x E +1	kilogram (kg)
torr (mm Hg, 0^o C)	1.333 220 x E -1	kilo pascal (kPa)

*The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The gray (Gy) is the SI unit of absorbed dose.

ABSTRACT

Many military personnel who participated in the atmospheric nuclear-weapons testing program were subjected to contamination of skin and clothing by radioactive particles, and such contamination could have been an important contributor to external doses to skin. The main purpose of this report is to present a methodology to estimate doses to skin from dermal contamination due to a uniform deposition of airborne radioactive material in specific regions of the body. This methodology includes a model to estimate increases in doses due to long-term retention of radioactive material on skin when removal by showering is incomplete. The primary focus of this report is estimation of doses from exposure to electrons (beta particles) emitted by radionuclides on the body surface. Estimation of doses from radionuclides that emit alpha particles also is considered. Models to estimate doses to skin from dermal contamination in various scenarios are described, including exposure to descending fallout from a nuclear weapon detonation and exposure to material resuspended from the ground surface by different human activities or the wind. Available data that can be used to estimate dermal contamination by airborne particles are discussed and summarized, including studies of deposition and retention of volcanic ash on human subjects in Costa Rica, studies using wind tunnels, studies involving direct contact with soil, and largely theoretical considerations of the effect of particle size. For each model developed in this report, recommended parameter values are provided as point (deterministic) estimates and as probability distributions to represent their uncertainty. Example calculations of doses to skin from beta-emitting radionuclides are used to investigate exposure scenarios in which the dose from dermal contamination is at least a significant fraction of the dose from exposure to radionuclides on the ground surface, situations in which inefficient showering can result in large increases in doses compared with an assumption of complete removal of contamination in the first shower, and uncertainties in estimated doses from dermal contamination and their sensitivity to uncertainties in model parameters. Doses to skin from contaminated clothing and from dermal contamination by direct contact with contaminated objects (including soil) also are discussed but are not treated in detail. The development of models and recommendations on parameter values in this report on the basis of limited data illustrates the importance of judgment in estimating doses to skin from dermal contamination.

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1. INTRODUCTION

Many military personnel who participated in the atmospheric nuclear-weapons testing program were subjected to contamination of skin and clothing by particles carrying beta-emitting radionuclides, and such contamination could have been an important contributor to external doses to skin. Deposition of radioactive particles on skin and clothing may have occurred as a result of exposure to descending fallout from detonation of a nuclear weapon or exposure to radioactive material that was resuspended from the ground surface by winds, by human activities (e.g., vehicular traffic), or by the blast wave produced in another detonation. Contamination of skin and clothing also may have occurred as a result of direct contact with contaminated objects or contaminated soil on the ground.

A committee of the National Research Council (NRC 2003) reviewed the methodology used by the Defense Threat Reduction Agency (DTRA) and its contractors to estimate doses to military participants in the atmospheric weapons testing program. The NRC committee's review indicated that none of the estimated doses to skin in any exposure scenarios included electron doses due to contamination of skin or clothing, even though the possible importance of this exposure pathway has been acknowledged (Barss 2000).

The main purpose of this report is to present a methodology that can be used to estimate doses to skin from dermal contamination due to a uniform deposition of airborne radioactive material in specific regions of the body.[1] This report focuses on doses from electrons (beta particles) emitted by radionuclides deposited on skin or clothing, but doses from radionuclides that emit alpha particles also are discussed. Section 2 summarizes various experimental data related to deposition and retention of particles on skin. Section 3 presents modeling approaches to estimate levels of dermal contamination and doses to skin. Following a description of the general approach in Section 3.1, models are developed that apply to descending fallout from a nuclear weapon detonation (Section 3.2), deposition of radioactive material that is resuspended from the ground surface (Section 3.3), or direct contact with contaminated objects or contaminated surface soil (Section 3.4). Section 3 also presents models to estimate the effects of inefficient showering on doses to skin from dermal contamination (Section 3.5) and to estimate

[1] For purposes of estimating dose, "skin" refers to radiosensitive tissues in the basal layer, which is the inner layer of the epidermis containing basal cells that continually divide to produce squamous cells.

doses from alpha-emitting radionuclides deposited on skin (Section 3.6). For each modeling approach discussed in this report, Section 4 provides recommended parameter values, including point (deterministic) estimates and probability distributions to represent their uncertainty.

Doses to skin from contamination of clothing by beta-emitting radionuclides are discussed in Section 5. The importance of electron doses to skin from dermal contamination relative to doses to skin from exposure to beta-emitting radionuclides on the ground surface in various exposure scenarios is investigated in Section 6. Section 7 provides a brief summary of developments in this report and highlights important conclusions.

This report includes several appendices. Appendix A presents a summary of data that can be used to estimate soil loadings on skin and clothing resulting from different human activities, data on the surface area of skin in different regions of the body, and data on resuspension factors associated with natural and human stresses. Appendix B describes an alternative approach to estimating doses to skin due to deposition of radioactive material that is resuspended from the ground surface. Appendix C provides a summary of parameter values that were used to investigate the importance of electron doses to skin from dermal contamination compared with doses from exposure to beta-emitting radionuclides on the ground surface in a variety of exposure scenarios. Appendix D provides data and modeling details on the efficiency of showering in removing deposited material from skin and the effect of inefficient showering on doses to skin from dermal contamination. Finally, Appendix E provides example calculations of electron doses to skin from dermal contamination, including quantification of uncertainties in estimated doses and investigations of the sensitivity of uncertainties in estimated doses to uncertainties in individual parameters.

2. REVIEW OF DERMAL CONTAMINATION STUDIES

Doses to skin from dermal contamination depend on the extent of deposition and retention of radioactive material on skin. This section summarizes the findings of experimental and theoretical studies on deposition and retention of particles on skin. These findings are important in developing modeling approaches presented in Sections 3.1 to 3.4. Some of the data that were extracted from those studies and used to develop estimates of model parameters are presented and discussed in this section. Additional data are presented in Appendix A.1.

Various kinds of particles can deposit and accumulate on skin, including soil particles with different percentages of clay, loam or sand, ash particles, debris from a weapon detonation, or dust particles. Different types of particles have been used in studies of dermal contamination. The type of particle is mentioned when known, and the effect of particle type on levels of dermal contamination is discussed to the extent possible. When the particle type is not specified, the term “soil particle,” “dust particle,” or simply “particle” is used.

Doses from radioactive particles deposited on skin depend on the specific activity (activity per unit mass) of the particles (μCi g^{-1}), the mass of particles per unit area of skin (g cm^{-2}), the dose rate per unit activity concentration on skin (rem h^{-1} per μCi cm^{-2}_{skin}), and the exposure time (h).[2] In the NTPR Program, doses to skin usually are calculated using estimates of activity concentrations on skin (μCi cm^{-2}_{skin}) that are obtained by methods that avoid use of the specific activity of particles, which generally is unknown in cases of exposure of military participants at atmospheric weapons tests.

The activity of radionuclides in the environment where military participants were exposed usually is expressed in terms of an activity concentration on the ground (Ci m^{-2}_{ground}), which is estimated on the basis of historical measurements of external exposure rates in air. Thus, an approach to estimating doses from dermal contamination should use such a quantity.

Different types of studies have investigated the accumulation of soil particles on skin under various conditions. Section 2.1 describes studies that provide information on the mass

[2] Except as noted, conventional units of activity (Ci) and equivalent dose (rem) are used in this report to be consistent with units used in the Nuclear Test Personnel Review (NTPR) Program to assess doses to military participants at atmospheric weapons tests.

loading of particles per unit area of skin (g cm^{-2}) by any means (e.g., handling of different types of soil or performing common activities, such as gardening). Section 2.2 describes measurements of interception and retention of airborne particles on skin, which is specified as a fraction of the mass of particles deposited per unit area of soil (g cm^{-2}_{soil}) that is intercepted and retained by a unit area of skin.

2.1. Dust Loading on Skin

Doses to skin from dermal contamination depend on the mass of radioactive particles that adhere to skin per unit area. A comprehensive review of studies of adhesion of soil to skin under a variety of conditions was performed by the U.S. Environmental Protection Agency (EPA 1997). Two important studies are those by Driver et al. (1989), which was included in EPA's review, and Sheppard and Evenden (1994). Those studies describe measurements of adhesion of soil particles under conditions of direct contact of skin with soil (e.g., concentrations of soil on hands resulting from touching or handling soil). Other studies considered in EPA's review investigated accumulation of soil on skin during various activities, such as playing outdoor sports, gardening, farming, or engaging in archeological investigations. Studies reviewed by EPA (1997) provide important information on the efficiency of soil adhesion to human skin in different situations, including resuspension from the ground surface by walking, running, or mechanical disturbances. In addition to EPA's review, Kochendorfer and Ulberg (1967) published a largely theoretical study of human exposure to particulate debris from break-up of nuclear-powered aerospace vehicles that provides insight into important aspects of particle interception and retention on skin. Other experiments include those reported by Black (1962), who studied accumulation of soil on clothing and skin of military personnel who were dressed in full combat fatigues while crawling under simulated combat conditions for several hundred feet through two test areas (bare soil and dry clipped grass) that were contaminated with soil particles labeled with ^{140}La.

The main findings of the studies noted above are summarized as follows.

- Particle size is the most important parameter that determines adhesion to skin. The smaller the particle size, the more efficient the adhesion to skin.

- Particles of diameter[3] less than 2 μm, which are of the same scale as surface roughness features of skin, can be incorporated into the skin surface and be very resistant to cleaning (especially clay particles).

- Particles of diameter greater than 50 μm adhere to bare skin (i.e., dry particles on dry skin) much less efficiently than smaller particles (Sheppard and Evenden 1994). However, larger particles can be trapped by hair and retained on or close to skin.

- Soil loadings on skin of the hands of adults under conditions of contact of dry skin with dry soil measured by Driver et al. (1989) were about 1.4 mg_{soil} per cm^2_{skin} for particle sizes less than 150 μm, 1 mg_{soil} per cm^2_{skin} when the maximum particle size was increased to 250 μm, and 0.6 mg_{soil} per cm^2_{skin} for unsieved soils. Particle size was the most important determinant of soil loading, while soil type and organic content were less important. Experiments by Sheppard and Evenden (1994) indicated soil loadings of 0.2 to 2.0 mg_{soil} per cm^2_{skin}, with a typical value of 0.8 mg_{soil} per cm^2_{skin}, for 11 types of dry soils sieved through a 5-mm mesh. Thus, a typical soil loading of dry soil on dry skin under contact conditions is about 1 mg_{soil} per cm^2_{skin}.

- Lower soil loadings occur if skin is partially protected by clothing or if contact with soil is inadvertent. Studies in which the amount of soil on skin was measured after activities such as gardening, farming, and playing sports (EPA 1997) or performing combat crawling (Black 1962) indicated that soil loading varies in different regions of the body. The highest accumulations of soil were observed in places where skin contacts soil (e.g., hands, wrists, knees, elbows) or in wrinkles of skin. The lowest soil loadings were observed on skin of the face.

- Soil loading on skin depends on an individual's activity [see Appendix A.1, Tables A-1 and A-2 reproduced from EPA (1997) and Tables A-3 and A-4 based on data reported by Black (1962)]. The largest soil loadings were observed for such outdoor workers as gardeners, farmers, or earth-moving machine operators (up to 0.7 mg cm^{-2} on hands), followed by individuals who engaged in outdoor recreation activities (e.g., soccer,

[3] In contrast to studies of aerosols, in which different types of diameters can be defined to capture the aerodynamic properties of particles, the term "particle diameter" is used in this report as an indicator of the physical size of particles, mainly to differentiate small particles from large particles.

football, rugby; up to 0.4 mg cm^{-2} on hands) and individuals who engaged in indoor activities (e.g., greenhouse workers; up to 0.04 mg cm^{-2} on hands).

- Soil loading on clothing can be 10 to 100 times greater than on skin (0.5 to 13 mg cm^{-2}) when clothing is contaminated by contact (e.g., after combat crawling). Soil loading on clothing greater than 5 mg cm^{-2} has the appearance of "caking" (Black 1962).

- Experiments by Sheppard and Evenden (1994) also indicated that typical soil loadings on skin resulting from touching soils with bare hands increase to about 2 mg_{soil} per cm^2_{skin} when soil is moist or wet. At soil loadings of 2 mg_{soil} per cm^2_{skin} or more, soil is visible on skin and individuals would normally wash their hands, which would lead to short retention times on skin. One can infer from those experiments that if soil is moist, the soil loading under conditions of direct contact with surface soil may increase from about 0.8 mg_{soil} per cm^2_{skin} to about 2 mg_{soil} per cm^2_{skin}, or by a factor of about 2.5.

- In the study of military personnel by Black (1962), perspiration was noted visually to have a marked effect on soil loading on skin. Those subjects whose skin was dampened by perspiration showed high soil loadings. However, as soon as skin dried, much of the soil dropped off. No quantitative statements were made by Black (1962) to indicate a relationship between soil loading and the amount of moisture on skin. In the absence of data, one could assume that accumulation of dry soil particles on moist skin is similar in magnitude to accumulation of moist soil on dry skin.

- Kochendorfer and Ulberg (1967) described results of an experiment performed at Oak Ridge National Laboratory (ORNL) by Fish et al. (1964) that was designed to determine the duration of retention of particles on skin. Those studies used wax and plastic spheres with diameters ranging from 50 to 1,000 μm that were loaded with fluorescent powder. The retention time was found to depend on surface conditions of skin, including oiliness and dampness (as from perspiration), the weight of particles, and the level of activity of the individual. However, no quantitative relationship between the degree of moisture or oiliness of skin and the retention time was reported. The number of particles remaining on skin was found to decrease exponentially with time, and the mean retention time on skin decreased with increasing particle diameter from 3 to 6 hours for 60 μm particles to 1.5 to 3 hours for 1,000 μm particles. The mean retention time for 40 μm particles was

- Experiments by Sheppard and Evenden (1994) used soils labeled with uranium. Since uranium was added to soil,[4] it is likely that the uranium accumulated on the surface of soil particles. Those experiments indicated that the specific activity of soil (activity of uranium per unit mass of soil) retained on skin is greater than the specific activity of labeled soil. This enrichment of specific activity probably was due to the greater retention of smaller particles on skin noted above. Because uranium presumably was distributed on the surface of soil particles, smaller particles had a higher specific activity than larger particles. Thus, skin preferentially retains particles with higher specific activity when radionuclides are concentrated on the surface of particles. Enrichment factors, defined as ratios of the specific activity of uranium in soil retained on skin to the specific activity of uranium in soil that contacts skin, for different soil types measured by Sheppard and Evenden (1994) are given in Table 2-1. Enrichment factors were as low as 1.2 to 2.4 for clay and loam soil particles and as high as 10 for sand particles.
- Soil type is less important in determining loading on skin than particle size or moisture content. For example, soil loading is not strongly influenced by the clay or organic content of soil.

2.2 Interception and Retention of Fallout Particles

A simple way to describe accumulation of airborne particles on skin is to quantify the fraction of the mass of incident particles that is intercepted and retained on skin. This section describes two sets of experiments that were designed to determine the magnitude of the interception and retention fraction of particles on skin. One set of experiments involved

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[4] Uranium oxide powder was dissolved in concentrated nitric acid to obtained uranyl nitrate solutions, which were used to treat soils.

deposition of ash following a volcanic eruption in Costa Rica; the other set involved specially prepared particles and controlled air flow in a wind tunnel.

2.2.1 Experiments Involving Deposition of Volcanic Ash

Interception and retention of airborne particles on skin of humans was studied in the aftermath of the eruption of the Irazu Volcano in Costa Rica. Experiments known as the CENIZA-ARENA (ash-sand) studies (Miller 1966a,b,c; 1967) consisted of measurements of the accumulation of ash and soil particles on subjects' skin, clothing and hair while performing normal activities (i.e., mostly walking or standing) during passage of a cloud of debris released from the volcano. The parameter of interest measured in those experiments is the skin contamination factor (a_h; in cm^2), which is defined as the mass of material that accumulated on a specific portion of an exposed body surface (Δw_h; in g) divided by the mass of the deposit per unit area on the ground surface during the period of exposure (Δm; in g cm^{-2}). This factor accounts for interception of airborne particles and initial retention on skin. Thus, it accounts for effects of weathering during the deposition event and shortly afterwards[5] until contamination was removed for measurement. Similar factors have been reported for accumulation of particles on clothing and in hair.

Costa Rica has a warm and humid climate. Irazu Volcano is located in the central highlands of Costa Rica, where the average temperature is 22–24°C (72–75°F), with little seasonal variation, and the average relative humidity is about 70%. Annual rainfall is about 200 cm, with the dry season from December to April and the rainy season from May to November. The personnel contamination experiments took place from June 15, 1965, to January 7, 1966 (Miller 1966c, pages 213–214). Given the warm temperatures and humid conditions, the observed interception and retention of particles on skin is expected to be enhanced compared with interception and retention when the humidity is low.

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[5] Personnel in those studies worked at various sites that were affected by ash fallout from the Irazu Volcano. Deposition on their skin ended when they boarded a Jeep that would take them to the location of the laboratory where ash deposited on skin was collected. We could not find statements about the time delay between the end of deposition and collection of ash from skin.

Ash particles from the Irazu Volcano eruption were similar in sizes and shapes to particles from nuclear weapons fallout. At diameters between 50 and 100 μm, for example, the similarity between the two types of particles was apparent from a comparison of photographs of volcanic ash particles and particles from nuclear weapons fallout collected near ground zero. From this point of view, the volcanic ash studies are relevant to modeling interception and retention of fallout particles produced by detonation of nuclear weapons.

Information obtained from the volcanic ash studies of relevance to assessing doses to skin from dermal contamination of military participants is summarized as follows:

- During some days when the CENIZA-ARENA studies took place, volcanic ash contained a distribution of particle sizes that was heavily weighted towards large particles (> 100 μm). That distribution of particle sizes is similar to the distribution of particle sizes in nuclear weapons fallout that deposits near ground zero and, thus, is relevant to dose reconstructions for military personnel at the Nevada Test Site (NTS). However, that particle-size distribution is different from particle-size distributions in fallout at larger distances from ground zero, which contained mostly smaller particles. Since military personnel who participated at nuclear weapons tests in the Pacific usually were located tens or even hundreds of miles from ground zero, an adjustment of estimates of interception and retention obtained from the volcanic ash studies to account for the preponderance of smaller particles is needed in such cases.
- In the CENIZA-ARENA studies, the particle-size distribution of volcanic ash that accumulated on skin, clothing or hair had a larger number of small particles compared with the particle-size distribution of ash that deposited on the ground. Particles with diameters as low as 40 μm were identified on all individuals. For some individuals, particles sizes as low as 3 μm were detected.
- As summarized in Table 2-2, values of the skin contamination factor (a_h) measured in the CENIZA-ARENA studies varied over the following ranges:
  - Face: 2.5–19 cm^2 [geometric mean (GM) of 7 cm^2; two measurements];
  - Forearms and hands: 66–172 cm^2 (GM of 115 cm^2; three measurements);
  - Forehead: 7.5 cm^2 (one measurement);

- Inside ears: 5.8–6.8 cm^2 (GM of 6 cm^2; three measurements);
- Hair, male, crew cut: 10–585 cm^2 [eight measurements, three with incomplete collection of material; as indicated in Fig. 2-1, the remaining five measurements follow a lognormal distribution with a GM of 182 cm^2 and geometric standard deviation (GSD) of 2.8];
- Hair, male, medium cut: 17–620 cm^2 [eight measurements, two with incomplete collection of material; as indicated in Fig. 2-1, the remaining six measurements follow a lognormal distribution with a GM of 163 cm^2 and GSD of 2.56];
- Clothing (blouse): 385 cm^2 (one measurement);
- Range of all measurements on skin and hair: 2.5–620 cm^2.

- In general, larger particles were retained to a greater extent on skin covered with hair than on skin without hair. Values of a_h for forearms were relatively large and similar to those observed for hair; they probably reflect an enhanced retention due to the presence of hair on forearms.
- The most numerous measurements of a_h were reported on the hair of two males, with different styles of haircut. These data provide an indication of the variability of a_h for a single individual exposed at different times. As shown in Fig. 2-1, measured skin contamination factors for hair for the two individuals follow lognormal distributions with similar GMs (182 and 163 cm^2) and GSDs (2.8 and 2.56). When the single measurement of a_h for hair for a third individual in Table 2-2 is included, the GM of all measurements combined is 164 cm^2, and the GSD is 2.45.

In applying data from the studies of interception and retention of volcanic ash particles on skin to estimation of doses to skin from exposure to nuclear weapons fallout, it is important to understand the limitations of the data. The main issues that may affect how data from these studies are applied in estimating doses to military participants are summarized as follows:

- Values of the skin contamination factor (a_h) were determined only under conditions of standing or walking.

- Values of the skin contamination factor were determined only on limited portions of the body (i.e., forearms and hands, face, forehead, hair, and inside the ears).
- The definition of the "face" is not clear. It may be reasonable to assume that "face" includes the forehead, even though values of a_h for "forehead" were reported separately.
- There are no measured a_h values for skin of the torso or legs.
- Even if a_h values for bare skin of the torso or legs were available, deposition of particles on skin in those regions of the body often occurs in the presence of clothing, which reduces, but does not eliminate, skin contamination. Clothing could act as a filter to remove large particles and prevent their deposition on skin. However, fine particles have a greater tendency to travel with the flow of air under clothing, especially during the summer when clothing is worn loosely.
- Additional doses to skin can result from accumulation of radionuclides on clothing. Thus, it is important to quantify activity concentrations on clothing due to contamination by descending or resuspended fallout or by direct contact with contaminated materials. The CENIZA-ARENA studies offer only one measurement of the skin contamination factor for clothing, without specifying the part of clothing for which a_h was measured. A discussion of contamination of clothing is presented in Section 5.

2.2.2 Wind-Tunnel Experiments

In a set of experiments involving controlled conditions in a wind tunnel, Asset and Pury (1954) studied deposition of small, wind-driven particles on human skin. Those experiments used specially prepared spherical particles with median diameters less than 10 μm that were dispersed in an air flow with controlled wind speed. Results of those studies are given in Table 2-3. An interpretation of findings of the wind-tunnel studies as they may apply to dermal contamination of military participants is summarized as follows:

- Forearms of volunteers were exposed for 10, 15 or 30 minutes to particles with mass median diameters (MMD) of 1.3 or 6.5 μm that were carried by simulated winds at speeds of either 2 or 5 miles per hour (mph). The aerosol used was triphenyl phosphate

- Retention of particles was enhanced on the hairy part of forearms, compared with the hairless part. Retention increased when the wind speed was increased from 2 to 5 mph, an effect which was attributed to the increased number of particles impacting the skin.

- An efficiency of particle retention, defined as $E = m/A$ where m is the mass of aerosol deposited per unit area of forearm during exposure and A is the mass of aerosol that passed through a unit area whose plane is perpendicular to the direction of flow, was estimated. This efficiency of retention is similar to an interception and retention fraction discussed in Section 3.2, which is estimated by dividing a skin contamination factor (a_h) obtained in the volcanic ash studies described in Section 2.2.1 by the surface area s of skin in the region of the body where a_h was measured. The efficiency of retention of 6.5 μm particles varied from 0.54 to 0.9% at a wind speed of 5 mph (2.2 m s^{-1}), and a value of 0.17% was estimated at a wind speed of 2 mph (0.89 m s^{-1}). There was no measurable accumulation on skin when 1.3 μm particles were used, which indicates that very small particles ($d < 3$ μm) carried by winds are transported around the body with the air flow, thus resulting in a probability of impaction of essentially zero.

- Landahl (1944), as cited by Asset and Pury (1954), performed similar experiments using particles with an MMD of 4.5 μm, but having a wider particle-size distribution with a maximum diameter of 70 μm. Efficiencies of retention of about 2% at a wind speed of 5.5 mph (2.5 m s^{-1}) were reported. The difference in results compared with those obtained by Asset and Pury (1954) was attributed to differences in the particle-size distributions in the two experiments. Only 7% of the particles in experiments by Asset and Pury (1954) were larger than 10 μm (maximum diameter of 20 μm), while 20% of the particles in the experiments by Landahl (1944) were larger than 10 μm (maximum diameter of 70 μm).

The wind-tunnel experiments summarized above are not entirely relevant to assessments of doses from deposition of nuclear weapons fallout because they used very small particles, they were performed under dry conditions using specially prepared spherical particles and constant wind speeds, and they involved only short exposure times (less than 30 minutes).

2.2.3 Experiments Involving Dermal Contamination in Indoor Environments

More recently, contamination of human skin in indoor environments was studied by Fogh et al. (1999). The purpose of that study was to gather information that could be used to estimate doses to skin from dermal contamination by radioactive particles released from a nuclear facility. The experiments involved particles with diameters ranging from 0.02 to 20 μm in indoor dry environments with little or no air movement. Particles were labeled with stable tracers that could be activated by neutrons or with fluorescent tracers, depending on the type of study. The various experiments included studies of deposition of particles on skin, hair or clothing of human volunteers and on samples of rat skin or other materials (filter paper, felt and polyethylene) mounted on fixed cylinders. Studies of dermal contamination investigated deposition of particles, contamination by contact transfer, retention and clearance of particles, and the removal efficiency of wiping, washing, waxing or vacuuming. Studies of contamination on clothing or hair investigated deposition and clearance of particles.

Deposition of particles on skin, hair or clothing was described in terms of a deposition velocity, defined as the flux density of particles toward the body surface divided by the concentration in air. The flux density of particles toward the body surface refers to the mass of particles that impact and are retained on the surface at a particular location and is given by the mass deposited and retained per unit area divided by the exposure time. Measured deposition velocities on skin under dry, windless conditions in a test chamber increased as the particle size was increased from 2.5 to 8 μm. Fogh et al. (1999) speculated that a cause of the lower deposition velocities of smaller particles was the greater effect of convective currents generated by body heat in deflecting those particles around the body surface. Reported deposition velocities on skin are discussed further in Section 4.4, and information on contamination of clothing obtained from that study is discussed in Section 5.2.

Results of experiments by Fogh et al. (1999) probably cannot be used to assess doses from nuclear weapons fallout. Those studies were performed in dry indoor environments under conditions very different from those encountered at nuclear weapons testing sites. The experiments involved little or no air movement, a situation very different from that experienced in the field by military participants. Particle sizes used in those studies are smaller than the size of most fallout particles (i.e., less than 20 μm, with one of the tracers attached to particles with a median diameter of 0.7 μm). At those particle sizes, and given that there was no air movement and the volunteers were mostly stationary, deposition probably was increased by electrostatic forces, which should be less important at larger particle sizes.[6]

Another difficulty is the presentation of results of those experiments in terms of a deposition velocity. To use a deposition velocity in calculating dermal contamination, an estimate of an air concentration or time-integrated air concentration at the location of an exposed individual is needed. While measurements of air concentration may be common at nuclear facilities, estimates of dose to military participants rely on measurements of external exposure rates ($R\ h^{-1}$) following deposition of fallout on the ground surface. An exposure rate would need to be converted to a concentration in air, e.g., by using an estimate of the deposition velocity that could have produced the activity concentration on the ground surface that resulted in the measured exposure rate. Such a procedure would involve significant uncertainties. In addition, both deposition velocities (on skin or on the ground) depend on particle size, so that application of those results to exposure to larger particles in nuclear fallout adds more uncertainty. These uncertainties would be larger than uncertainties associated with application of data from the volcanic ash studies, which directly relate the mass of material deposited on skin to the mass of material deposited on the ground. Thus, results of the volcanic ash studies with respect to deposition on skin or clothing are used directly in this report.

Studies by Fogh et al. (1999) also provide information on the efficiency of removal of contamination from skin by wiping or washing. This information is discussed in Appendix D.2.2.6.

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[6] The importance of electrostatic forces in determining deposition of small particles on skin was indicated by measurements which showed that the deposition velocity on skin of the hand was lower if the hand was electrostatically grounded (Fogh et al. 1999; Table 4.3).

2.2.4 Consideration of Effects of Particle Size

Particle size probably is the most important parameter that affects interception and retention on skin. In a theoretical part of their paper, Asset and Pury (1954) indicated that the larger the particle diameter, the larger the probability of inertial impaction. At the same particle diameter, the probability of inertial impaction also increased with increasing wind speed and particle density. Kochendorfer and Ulberg (1967) also noted an increase in the probability of inertial impaction with increasing particle size. They found that the probability that a particle will stick to skin for a significant length of time decreases as $1/d$, where d is the particle diameter. This relationship applies at least for particles of diameter greater than 100 μm.

Kochendorfer and Ulberg (1967) pointed out a compensatory effect of particle size. Specifically, for particles of diameter greater than 10 μm, the larger the particle size, the larger the probability of impaction on skin but the lower the initial retention due to reduced adhesion.[7] According to those investigators, the dominant process is the decrease in initial retention with increasing particle size—i.e., when the effect of particle size on the probability of impaction is combined with the effect on adhesion, the overall result is a decrease in initial interception and retention with increasing particle size. Given that estimates of the skin contamination factor (a_h) obtained in the volcanic ash studies apply to particle-size distributions that included particles of diameter up to 300 μm with a median diameter of 50 to 80 μm, it is possible that exposure to a distribution of particles weighted towards smaller sizes would result in a higher level of skin contamination and, thus, larger values of the skin contamination factor, because smaller particles adhere to skin better than larger particles.

For very small particles (diameter less than 10 μm), the wind-tunnel studies by Asset and Pury (1954) and the indoor deposition studies by Fogh et al. (1999) seem to indicate that initial deposition and retention increases with increasing particle size. The authors of those studies suggested that very small particles have a low probability of impaction on the body surface due to their transport in air currents that flow around the body. This explanation is consistent with

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[7] A lower initial retention of larger airborne particles due to reduced adhesion is consistent with the reduced soil loading at larger particle sizes under conditions of direct contact of skin with soil reported by Driver et al. (1989) and discussed in Section 2.1.

observations that very small particles that are inhaled can largely avoid obstacles and filters in the respiratory tract and are deposited mainly in regions of the deep lung (ICRP 1994).

Studies summarized above indicate that interception and retention of airborne particles on skin may increase with increasing particle size up to about 10 μm, but is expected to decrease with increasing particle size at diameters greater than about 50 to 100 μm. Military personnel exposed to weapons fallout encountered particles with size distributions that were heavily weighted toward particles of diameter greater than 10 μm. Exposure to previously deposited fallout that was resuspended by winds involved particles of diameter about 100 μm or less (Sehmel 1984), with most resuspended fallout particles also larger than 10 μm. Thus, for exposure situations of concern to this report, interception and retention can be considered to decrease with increasing particle size, at least at diameters greater than about 50 to 100 μm.

Table 2-1. Specific activity enrichment ratios from experiments with soils labeled with uranium (Sheppard and Evenden 1994)

Soil type[a]	Clay content (%)	Enrichment ratio[b] (adhesion to hands)
Clay	33	2.0
Heavy loam	24	2.3
Garden	18	1.2
Medium loam	15	7.8
Rich loam	13	2.4
Carbonated loam	12	1.9
Medium sand	6	2.7
Fine sand	4	8.4
Limed sand	3	9.9
Acid sand	1	10.4
Peat	<1	2.9

[a] Soils were dry and sieved through a course 5-mm mesh. Thus, particle diameters ranged over orders of magnitude.

[b] Ratio of activity of uranium per unit mass in soil on skin to activity of uranium per unit mass in whole soil.

Table 2-2. Skin contamination factors (a_h) obtained from studies of deposition of volcanic ash in CENIZA-ARENA experiments in Costa Rica (Miller 1966c)

Individual / Sample description	Date / Exposure duration (h)	Δm[a] (g ft^{-2})	Δw_h[a] (g)	$a_h = \Delta w_h/\Delta m$[a] (cm^2)
Deposition on skin only				
WBL; inside ears, spray-wash	6-15 / 2.93	5.1	0.037	6.8
CFM; inside ears, spray-wash	6-15 / 2.93	5.1	0.032	5.8
CFM; inside ears, spray-wash	1-7 / 5.00	1.6	0.010	6.0
CFM; forehead, spray-wash	6-16 / 2.47	13.8	0.11	7.5
CFM; face, wash plus shave	8-11 / 7.10	15.1	0.040	2.5
CFM; face; spray-wash	1-7 / 5.00	1.6	0.032	19
CFM; forearms; spray-wash plus rubbing	10-6 / 7.00	1.1	0.16	135
CFM; forearms and hands, spray-wash	1-7 / 5.00	1.6	0.11	66
CFM; forearms and hands, spray-wash	1-7 / 0.92	0.16	0.029	172
Deposition on hair and skin				
WBL; hair & face, spray-wash	1-7 / 4.00	1.20	0.24	190
WBL; hair & face, spray-wash +dry combing	1-7 / 4.00	1.20	0.32	247
Deposition on hair[b]				
WBL; hair, spray-wash plus wet brushing	6-16 / 2.47	13.82	1.00	67
WBL; hair, spray-wash[c]	6-16 / 2.47	13.82	0.15	10
WBL; hair, spray-wash plus brushing	6-15 / 2.93	5.14	1.20	216
WBL; hair, spray-wash[c]	6-15 / 2.93	5.14	0.99	179
WBL; hair, dry brushing	12-9 / 0.67	0.042	0.0026	57
WBL; hair, dry combing plus spray-wash	1-7 / 0.92	0.16	0.071	419
WBL; hair, dry combing[c]	1-7 / 0.92	0.16	0.035	206
WBL; hair, spray-wash	1-15 / 0.25	0.77	0.49	585
JLJ; hair, spray-wash with combing	1-7 / 5.00	1.58	0.16	96
CFM; hair, spray-wash plus wet brushing	6-16 / 2.47	13.82	0.71	48
CFM; hair, spray-wash plus brushing	6-15 / 2.93	5.14	0.65	118
CFM; hair, spray-wash[c]	6-15 / 2.93	5.14	0.50	90
CFM; hair, spray-wash	6-16 / 2.47	13.82	0.25	17
CFM; hair, dry brushing	8-11 / 7.10	15.13	1.57	97
CFM; hair, spray-wash with combing	1-7 / 5.00	1.58	0.24	143
CFM, hair, spray-wash[c]	1-7 / 0.92	0.16	0.11	620
CFM, hair, spray-wash	1-15 / 0.25	0.77	0.33	393
Deposition on clothing				
JLJ, blouse, spray-wash	1-7 / 2.67	0.80	0.33	385

[a] Δm is mass of ash particles deposited per unit area of ground surface, and Δw_h is mass of ash particles accumulated on sampled area of skin, hair or clothing. Skin contamination factor (a_h) is given in units of cm^2 used in this report.

[b] Hair cut: WBL, crew, male; CFM, medium, male; JLJ, medium, female.

[c] Measurements with incomplete collection of material; data were not used in our analysis.

Table 2-3. Experimental details and summary of estimates of efficiency of particle retention on skin obtained in wind-tunnel studies

Location	Exposure duration (min)	No.of runs	Particle size[a] (μm)	Wind speed (mph)	Efficiency of particle retention[b] (%)	
					Average	Range
Asset and Pury (1954)[c]						
Effect of exposure duration						
Hairy surface of forearm	10	7	6.5	5	0.58	1 zero; 0.23–0.93
Hairy surface of forearm	15	3	6.5	5	0.54	0.13–0.66
Hairy surface of forearm	30	4	6.5	5	0.64	0.33–0.95
Effect of hair						
Hairy surface of forearm	15	7	6.5	5	0.63	0.43–0.80
Hairless surface of forearm	15	10	6.5	5	0.07	7 zeros; 0.11–0.37
Effect of wind speed and particle size						
Hairy surface of forearm	20	10	1.3[d]	5	0	none detected
Hairy surface of forearm	20	11	6.5	2	0.17	6 zeros; 0.18–0.65
Hairy surface of forearm	20	8	6.5	5	0.9	0.39–1.9
Landahl (1944)[e]						
Hairy surface of forearm		10	4.5	5.5	1.9	Not reported

[a] Mass median diameter of distribution of particle sizes.

[b] Ratio of mass of particles deposited per unit area of forearm to mass of particles that passed through unit area of plane perpendicular to direction of flow.

[c] Unless otherwise noted, about 7% of mass was carried on particles of diameter greater than 10 μm and maximum diameter was 20 μm.

[d] About 5% of mass was carried on particles of diameter greater than 2.6 μm; maximum diameter was not reported. By assuming that particle-size distribution was lognormal with median of 1.3 μm and 95th percentile of 2.6 μm, maximum particle size (taken to be close to 99.9th percentile) should have been about 5 μm.

[e] About 20% of mass was carried on particles of diameter greater than 10 μm, and maximum diameter was 70 μm.

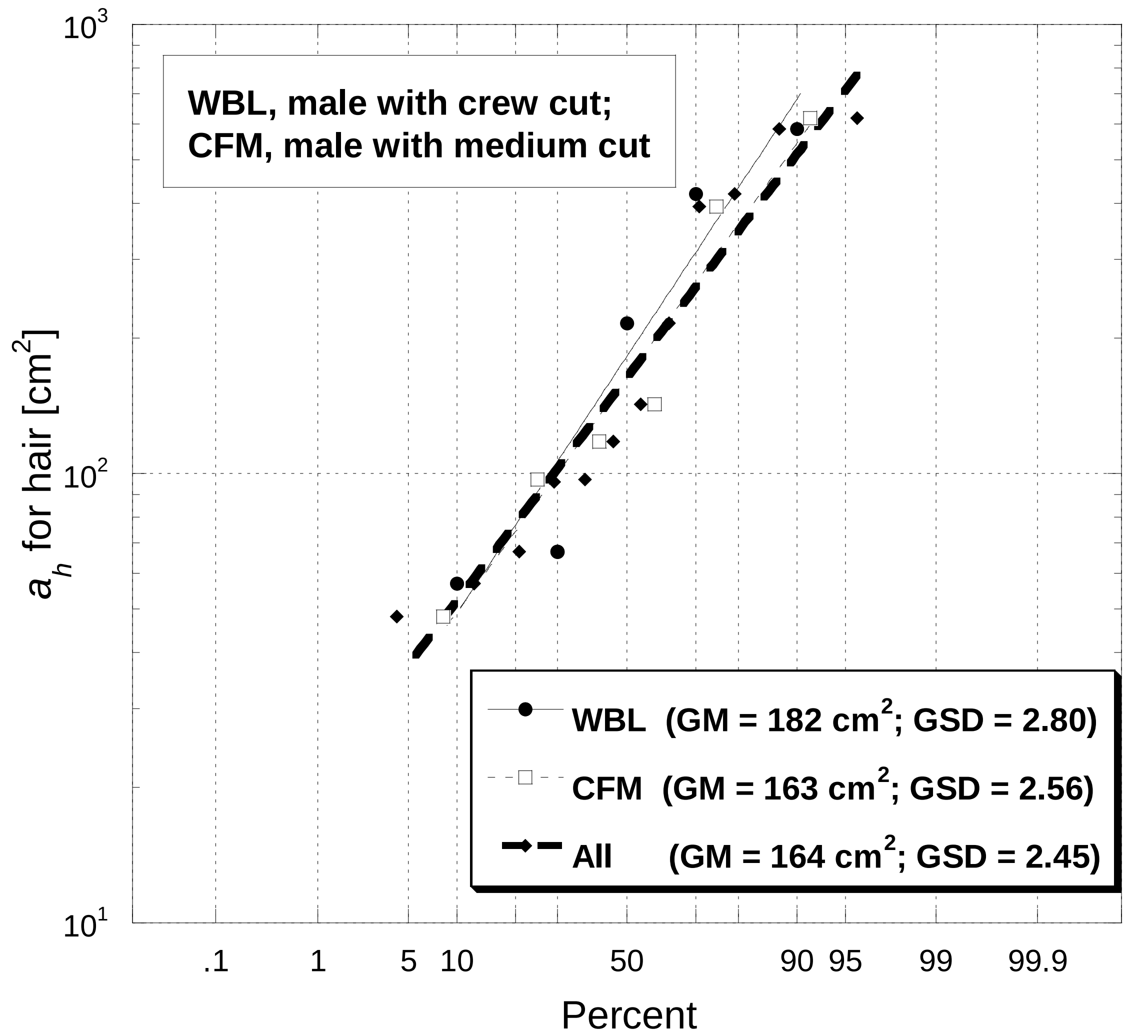


Figure 2-1. Variability of contamination factor, a_h, for hair obtained in studies of deposition of volcanic ash in CENIZA-ARENA experiments (Miller 1966b).

3. MODELS TO ESTIMATE DOSES TO SKIN FROM DERMAL CONTAMINATION

Models to estimate doses to skin from dermal contamination by radioactive material were developed on the basis of data obtained in the various studies summarized in Section 2. The general approach is described in Section 3.1. This approach is used to develop models for dermal contamination by descending fallout (Section 3.2), resuspension of old fallout (Section 3.3), and other activities (Section 3.4). The approach distinguishes between doses from exposure to a single radionuclide and exposure to a mixture of radionuclides in fallout.

Contaminants retained on skin are removed by washing, but the removal process is only partially efficient. An approach to modeling the effect of inefficient washing on doses to skin from dermal contamination is described in Section 3.5.

Models developed in this report are concerned primarily with estimating doses to skin from exposure to electrons emitted by radionuclides that are deposited and retained on skin or clothing. Emitted electrons of concern include continuous spectra of beta particles and internal conversion and Auger electrons of discrete energies. When mixtures of radionuclides in fallout from a nuclear weapon are deposited on skin or clothing, doses to skin from photons should be negligible compared with doses from electrons (Barss and Weitz 2006) and are not considered in this report. This report also considers doses from alpha-emitting radionuclides deposited on uncovered skin; the rationale for considering alpha doses to skin is discussed in Section 3.6.

All parameters in models developed in this report are defined in this section. Values of each parameter are discussed in Section 4 for several types of exposure scenarios that are defined according to the source of contamination (i.e., fallout or resuspended material), duration of deposition onto skin (i.e., acute deposition, single continuous deposition, or chronic long-term and intermittent deposition), particle size, humidity conditions, and wind speed.

3.1 Description of General Approach

The dose rate to radiosensitive tissues in the basal layer of skin from electrons or alpha particles emitted by radionuclides deposited on the body surface can be estimated as:

$$\dot{D}(t) = C_{skin}(t) \cdot DRF_{skin} \quad (3\text{-}1)$$

where

$\dot{D}(t)$ = dose rate to skin at time t (rem h^{-1});

$C_{skin}(t)$ = activity concentration of radionuclides on skin at time t (μCi cm^{-2});

DRF_{skin} = dose-rate factor (dose rate per unit activity concentration of radionuclides deposited on skin) for electrons or alpha particles at assumed depth of radiosensitive tissues below the body surface (rem h^{-1} per μCi cm^{-2}).

In cases of exposure to descending fallout, skin is contaminated in a relatively short period of time. The activity concentration on skin reaches its maximum value at the end of the deposition event and then decreases over time by radioactive decay and other loss processes. For purposes of estimating dose from dermal contamination by descending fallout, the activity concentration on skin is assumed to reach its maximum value instantaneously. Equations that apply to an acute deposition of descending fallout are given in Section 3.2.

In contrast to exposure to descending fallout, estimation of doses to skin from dermal contamination by resuspension of nuclear weapon debris is modeled as a continuous process. Resuspension can occur as a natural phenomenon (i.e., resuspension by winds) or as a result of such human activities as vehicular traffic (e.g., marching behind a vehicle), take-off or landing of helicopters, and walking through a contaminated area. Deposition of resuspended fallout onto skin can take place over many hours or days. In such cases, the activity concentration on skin is a function of time determined by the rate of deposition and the rate of loss of radioactive material on skin. Doses to skin from a single day's deposition of resuspended material are calculated by integrating eq. (3-1), thus accounting for the dose during the period of resuspension and deposition on that day and the dose after deposition ceased (e.g., after leaving a contaminated area). Equations that apply to exposure to resuspended material are given in Section 3.3. Doses from many days of exposure to resuspended material can be estimated by summing doses received as a result of each day's deposition onto skin.

Skin contamination is reduced by washing. However, washing may not eliminate all contamination, especially smaller particles that become embedded in pores and creases of the skin. For example, Appendix D.2.2.4 discusses data on military participants for whom even a

vigorous showering did not reduce skin contamination by a large amount and repeated showers and washing occurred in an effort to achieve decontamination.

The modeling approach presented in Sections 3.2 to 3.4 provides estimates of dose from the time dermal contamination begins until the time of the first shower. In Section 3.5, a model is developed to estimate the additional dose received after the first shower from exposure to residual radioactive material that is not removed from skin by showering.

3.2 Contamination of Skin from Exposure to Descending Fallout

In this report, contamination of skin by descending fallout is treated as an acute event that is assumed to occur essentially instantaneously. This assumption is equivalent to an assumption that the dose to skin during the period of deposition by descending fallout is negligible compared with the dose after deposition ceases.

As indicated by eq. (3-1), dose rates to skin from deposition of descending fallout are proportional to the activity concentration of radionuclides on skin. The most common and reliable type of data obtained at locations where military personnel were exposed are measurements of external exposure rates (R h^{-1}), from which activity concentrations of radionuclides on the ground surface (Ci m^{-2}) are derived (Barrett et al. 1986). It is desirable to relate the activity concentration on skin to the derived activity concentration on the ground surface. In this study, we use an effective interception and retention fraction, AR_f, which represents the fraction of the activity concentration deposited on the ground surface that is intercepted and retained on skin. Using this parameter, the dose rate to skin at time t is given by:

$$\dot{D}(t) = C_{skin}(t) \cdot DRF_{skin} = C_{gs}(t) \cdot AR_f \cdot DRF_{skin} \tag{3-2}$$

where

$C_{gs}(t)$ = activity concentration of radionuclides in fallout deposited on the ground surface (μCi cm^{-2});

AR_f = effective interception and retention fraction (unitless).

The CENIZA-ARENA volcanic ash studies described in Section 2.2.1 provide data that can be used to estimate an interception and retention fraction, r (unitless), which is defined as the

ratio of the skin contamination factor a_h (cm^2), for which data are summarized in Table 2-2, to the area of skin s (cm^2) over which a_h was measured:

$$r = \left(\frac{a_h}{s}\right) \tag{3-3}$$

Data on the surface area of skin in different regions of the body are presented in Appendix A.2. The interception and retention fraction, r, represents the fraction of the <u>mass</u> of fallout particles deposited on the ground surface that is intercepted and retained on skin.

In contrast to r, AR_f is an <u>effective</u> interception and retention fraction that represents the fraction of the <u>activity concentration</u> of fallout deposited on the ground surface that is intercepted and retained on skin. As discussed in Section 2, interception and retention is affected by the amount of moisture on skin, the particle size, and the distribution of radionuclides on the surface or in the volume of fallout particles at the location of exposure. The effective interception and retention fraction, AR_f, accounts for the fact that exposure conditions for military personnel could have differed from exposure conditions in the volcanic ash studies. This parameter is calculated by adjusting the interception and retention fraction, $r = (a_h/s)$, estimated from the volcanic ash studies for the effects of moisture, enrichment of specific activity, particle size, and the distribution of radionuclides on particles as:

$$AR_f = \left(\frac{a_h}{s}\right) \cdot PS_a \cdot EM \cdot EF \cdot AW \tag{3-4}$$

where

PS_a = adjustment factor (unitless) to represent how retention on skin depends on particle size and to account for the difference between the particle-size distribution at a location of interest and the particle-size distribution for which a skin contamination factor (a_h) was measured;

EM = adjustment factor (unitless) to account for an increase in retention efficiency with increasing moisture on skin;

EF = specific-activity enrichment factor (μCi $g^{-1}{}_{skin}$ per μCi $g^{-1}{}_{ground}$) to account for experimental evidence indicating that the specific activity of soil retained on

skin is higher than the specific activity of soil on the ground when radionuclides are preferentially distributed on particle surfaces;

AW = activity-weight adjustment factor (unitless) to account for the difference between the activity and weight particle-size distributions in fallout.

These adjustment factors are discussed in more detail in Section 4.2.

The interception and retention fraction [r=(a_h/s)] is derived mainly from data obtained in the volcanic ash studies. Data from the wind-tunnel experiments presented in Section 2.2.2 are used as complementary information. Experimental conditions in the wind-tunnel studies (small particles, dry conditions, constant and unidirectional winds, and exposure durations of 30 minutes or less) differed from conditions in the volcanic ash studies (medium-to-large particles, humid conditions, variable wind speeds and directions, and exposure durations of hours). Thus, to apply an interception and retention fraction obtained from the wind-tunnel studies to military participants at atmospheric tests, values of parameters described above must be selected to adapt the conditions of those studies to the exposure conditions of military participants. When appropriate adjustments are made to data from the wind-tunnel studies, the interception and retention fractions obtained from the two studies are not inconsistent.

3.2.1 Dose from Single Radionuclide

The dose delivered to skin during a time period Δt after an acute fallout event at time T_0 can be estimated by integrating eq. (3-2). In the absence of showering or washing, the activity concentration on skin is reduced by radioactive decay and weathering (unintentional loss) of particles from skin. Radioactive decay is important for short-lived radionuclides and should be taken into account during the period after an acute deposition of fallout. Weathering can be important for large particles, which can fall from the skin or are easily removed by normal movement or light brushing. Weathering could occur during and after a deposition event. Weathering is much less important for small particles than for large particles (Fish et al. 1964). Small particles are lighter and thus are less affected by gravity, and they are harder to see on the skin, which reduces the chance of willful brushing or cleaning. Smaller, lighter particles also are more affected by electrostatic attraction than larger, heavier particles. Finally, very small particles can become embedded in skin imperfections and be very resilient even to washing.

By assuming that all particles retained on skin are sufficiently small that they are not easily removed by weathering, which is equivalent to assuming that skin contamination factors, a_h, measured in the volcanic ash studies include effects of weathering over a few hours, eq. (3-2) can be integrated to account only for radioactive decay after a deposition event. For a single radionuclide, the dose to skin (rem) during the period Δt in hours after an acute fallout event is:

$$D(\Delta t) = \int_{T_0}^{T_0+\Delta t} \dot{D}_0 \cdot e^{-\lambda_R (t-T_0)}\, \mathrm{d}t = C_{gs}^0 \cdot AR_f \cdot DRF_{skin} \cdot \frac{1-e^{-\lambda_R \Delta t}}{\lambda_R} \qquad (3\text{-}5)$$

where

T_0 = time after detonation when deposition of fallout occurs (h),

$\dot{D}_0$ = dose rate to skin at time T_0 (rem h^{-1}),

C_{gs}^0 = activity concentration of radionuclide on the ground surface at time T_0 (μCi cm^{-2})

λ_R = radionuclide decay constant (h^{-1}).

If the time Δt that contamination is retained on skin (e.g., before removal by showering) exceeds the radionuclide half-life by a factor of about six or more, the total dose is given by the initial dose rate divided by the radionuclide decay constant, independent of Δt. If the radionuclide half-life is long compared with Δt, the dose rate is approximately constant in time and the total dose is given by the initial dose rate multiplied by Δt. If the radionuclide has radioactive decay products, in-growth of all important progeny has to be taken into account using the Bateman equations.

3.2.2 Dose from All Radionuclides Combined

The number of radionuclides in fallout is large, especially at times shortly after a detonation. The dose from all radionuclides combined can be obtained by calculating the dose from individual radionuclides using eq. (3-5) and summing the results. However, that approach can lead to intensive calculations.

A more practical approach to estimating dose when many radionuclides are present in fallout is to use the empirical relationship that the activity concentration of all radionuclides

combined decreases with time after detonation as t^{-x}, where the exponent x in the power function often is about 1.2 at times shortly after detonation (Glasstone and Dolan 1977; Turner 1995). This relationship can be used to estimate doses from mixtures of radionuclides in fallout by applying equations given above, provided that the activity concentration represents the total activity concentration of all radionuclides combined. The specific-activity enrichment factor (*EF*), the dose-rate factor (*DRF*), and the activity-weight adjustment factor (*AW*) may be radionuclide-specific. However, as described in Section 4.2, values of these parameters can be specified that are representative of values for all radionuclides combined.

Using the power function for the time-dependence of the total activity of all radionuclides in fallout described above, the dose to skin during time period Δt after an acute fallout event (assuming negligible weathering of deposited radioactive material from skin) is given by:

$$D(\Delta t) = \int_{T_0}^{T_0+\Delta t} \dot{D}_0 \cdot T_0^{+x} \cdot t^{-x}\, dt = C_{gs}^0 \cdot T_0^{+x} \cdot AR_f \cdot DRF_{skin} \cdot \frac{T_0^{-x+1} - \left(T_0 + \Delta t\right)^{-x+1}}{x-1} \tag{3-6}$$

where

C_{gs}^0 = total activity concentration of all radionuclides on the ground surface at time T_0 after detonation (μCi cm^{-2}).

The total activity concentration on the ground surface at the time of deposition T_0 is estimated from measurements of exposure rate at various times after a detonation. Thus, if an activity concentration C_{meas} is obtained from measurements at time t_{meas}, the total activity concentration on the ground surface at time T_0 is estimated as:

$$C_{gs}^0 = C_{meas} \cdot t_{meas}^x \cdot T_0^{-x} \tag{3-7}$$

Equation (3-6) and other similar equations in this section could be written as a function of the concentration C_{meas} at the time an exposure rate was measured. However, since exposure rates usually were measured at different times t_{meas} and measurement times usually were not the same as the time of deposition of fallout, we prefer to use the activity concentration on the ground surface at the time of deposition, T_0, as an input to the model. Values of the effective interception and retention fraction (AR_f) and dose-rate factor (*DRF*) must apply to all radionuclides combined. Discussions in Sections 4.1 to 4.6 focus on estimating values of the interception and retention fraction $r = (a_h/s)$, its adjustment factors indicated in eq. (3-4), and

dose-rate factors that apply to all beta-emitting radionuclides in fallout combined. An example calculation for a single radionuclide is presented in Appendix E.1, and Appendix E.2 provides an example of a dose assessment that includes the combined effect of all beta-emitting radionuclides in fallout.

3.3 Contamination of Skin from Exposure to Resuspended Material

Deposition of radioactive particles on skin can occur not only by deposition of descending fallout from a nuclear weapon detonation, but also by deposition of resuspended old fallout. In the latter scenario, a fraction of the old fallout is lofted into the air by various mechanisms, and subsequent deposition leads to dermal contamination. Resuspension can occur as a result of various human activities, such as walking, driving a vehicle, take-off or landing of a helicopter, and detonation of weapons in areas where old fallout exists. A natural cause of resuspension is the wind.

Contamination of skin by descending fallout or by material resuspended by a nuclear detonation at a given location can be a short-term (acute) event. In contrast, resuspension by winds or some human activities can result in longer-term (continuous) contamination of skin over many hours or days. For example, military personnel who march behind vehicles can be exposed to material resuspended by the vehicles for as long as a maneuver lasts. Thus, modeling of contamination of skin by resuspension due to winds and certain human activities should reflect the continuous nature of deposition onto skin.

Detonation of a nuclear weapon in an area of old fallout is a special case of resuspension by human activity over a large region extending from ground zero. Exposure to large particles in descending old fallout that is resuspended by a nuclear detonation can be modeled as an acute event, in a manner similar to exposure to descending fresh fallout. However, exposure to resuspended small particles with fall times to Earth as long as several hours should be modeled as a continuous process.

Section 3.3.1 describes general properties of resuspended material. Section 3.3.2 presents an approach to estimating doses to skin due to resuspension of old fallout by such human activities as walking, driving a vehicle, or take-off or landing of a helicopter. Section 3.3.3

describes resuspension by winds. Finally, Section 3.3.4 addresses resuspension by a nuclear weapon detonation in an area of old fallout.

In most cases of exposure to resuspended material, our approach is based on a proposal by an analyst at Science Applications International Corporation (SAIC).[8] Given an activity concentration of radionuclides on the ground surface, we first estimate the activity concentration in air using a resuspension factor, which is defined as the ratio of the activity concentration in air to the activity concentration on the ground surface and normally is given in units of m^{-1}. We then estimate the flux of resuspended material incident on the body per unit area. In cases of wind-driven resuspension, resuspended material is carried towards the body by winds. In most cases of resuspension by human activities (and in the absence of significant wind), resuspended material is intercepted by the body at a speed given by its deposition velocity or the velocity of an individual relative to surrounding air; the one exception discussed in Section 3.3.4 involves exposure of forward observers at NTS to larger particles in old fallout that was resuspended by a nuclear detonation. In all cases, interception and retention fractions, r, obtained from the CENIZA-ARENA volcanic ash studies augmented by information from wind-tunnel studies (see Section 2.2) are used to estimate the fraction of the activity of resuspended material incident on the body that is ultimately retained on skin. Values of the adjustment factors that are applied to r [see eq. (3-4)] are chosen to represent the characteristics of resuspended material.

3.3.1 General Properties of Resuspended Material

Resuspension of material from the ground surface is influenced by many factors, such as particle size, material properties, topographical conditions, and meteorological conditions (Sehmel 1984). For instance, if soil is saturated with moisture, little or no wind-driven resuspension occurs. If soil is dry and the right meteorological conditions occur, dust devils can loft more particles than normally expected by wind-driven resuspension. The effect of these factors is acknowledged in the literature but has not yet been quantified in great detail.

An important factor in predicting doses from dermal contamination is the particle-size distribution of resuspended material, because interception and retention on skin and clothing

[8] Personal communication from J. Klemm, SAIC, McLean, Virginia (2004).

depends on particle size. Fallout at locations tens to hundred of miles from ground zero of a nuclear test contains mostly small particles with diameters of 100 μm or less (Glasstone and Dolan 1977; Sehmel and Hodgson 1976). Resuspension of this material will generate airborne particles with diameters less than 100 μm. At locations within a few miles of ground zero, diameters of fallout particles may range from a few to hundreds of μm (Miller 1969). However, under certain conditions (e.g., resuspension by winds or by such human activities as normal walking), resuspended fallout at locations close to ground zero will contain mostly smaller particles and, thus, a greater fraction of small particles than fallout on the ground surface.

Lee and Tamura (1981), citing Healy (1974) and Chepil (1945), state that resuspendable particles generally have diameters less than 100 μm. This should be the case for wind-driven resuspension under normal conditions (e.g., wind speeds less than 10 m s^{-1}, or 22 mph) (Garger et al. 1997a). However, very strong winds, blast waves from nuclear detonations, dust devils, or similar vigorous air movements can resuspend particles with diameters greater than 100 μm.

Sehmel (1984) showed that larger soil particles can be broken into smaller, respirable particles (< 10 μm) when subjected to the right amount of force. For example, to the extent that fallout particles are similar to soil particles, vehicular traffic could break larger particles into smaller ones before they are lofted into the air. However, even when large fallout particles are thrown into the air by vehicles without breakage, they probably would be lofted only to modest heights (perhaps a few meters or less) and would fall rapidly to the ground. Thus, at locations close to ground zero of a nuclear detonation (e.g., at NTS), it is expected that radioactive material resuspended by moving vehicles that could deposit on skin of nearby individuals contained mostly smaller particles compared with the size distribution of fallout particles.[9]

The blast wave produced in a nuclear detonation can create overpressures of many pounds per square inch at ground level over distances of thousands of feet from ground zero (Glasstone and Dolan 1977). Strong winds associated with a blast wave, which can be hundreds of miles per hour (Glasstone and Dolan 1977), and the thermal pulse at locations closest to ground zero presumably could loft even the largest radioactive particles. Two exposure situations can be distinguished in cases of resuspension by a nuclear detonation (Kocher et al.

[9] Another factor that limited resuspension of larger particles by vehicles at NTS was speed limits that were imposed on vehicular traffic to reduce resuspension.

2009). The first situation involves exposure to large particles that were redeposited on the ground within minutes after a detonation. Only forward observers who were located close to ground zero at the time of a detonation would be exposed to large particles in resuspended old fallout. A second situation involves exposure to small particles in resuspended old fallout that may have remained airborne for as much as a few hours after a detonation. Maneuver troops who entered an area impacted by a detonation after large particles had redeposited or forward observers who remained in that area for some time could have been exposed to small particles in those lingering dust clouds.

Thus, at NTS, individuals who encountered material that was resuspended by slow to moderate winds or slow moving vehicles or who encountered dust clouds that lingered after a nuclear detonation probably were exposed to particles with diameters that tended to be smaller than the diameters of fallout particles on the ground surface. Sizes of most resuspended particles should be less than 100 μm in such cases. Forward observers at locations close to ground zero during a test or other participants who were located in areas of strong winds (e.g., at locations of helicopter take-off or landing) presumably were exposed to resuspended particles with sizes from a few microns to hundreds of microns.

The amount of radioactive material on the ground surface that can be resuspended decreases with time due to leaching of soluble radionuclides, runoff, downward migration of particles, and other loss processes (Garger et al. 1997b). Consequently, resuspension may be less efficient a few years after an initial deposition of fallout than immediately after deposition. Exposure scenarios discussed in this report involve resuspension events that occurred at times from shortly after deposition (e.g., marching through a fresh fallout field) to as much as a few months or years (e.g., exposure to old fallout on a residence island in the Pacific).

3.3.2 Resuspension by Human Activities

This section discusses an approach to estimating doses to skin from dermal contamination due to resuspension of nuclear weapon debris by such human activities as vehicular traffic (e.g., marching behind a vehicle), take-off or landing of helicopters, or walking through a contaminated area. In contrast to descending fallout, which is modeled as an acute event, this

approach takes into account that deposition of resuspended fallout onto skin on a given day may take place over many hours, in which case resuspension and deposition should be modeled as a continuous process. Furthermore, in some exposure scenarios for military participants (e.g., exposure on a residence island in the Pacific), contamination of skin due to resuspension of fallout by human activities may have occurred each day over a period of weeks or months.

If human activities of interest are performed in an area that is contaminated at an average concentration (C_{gs}; μCi m^{-2}_{ground}), a resuspension factor (RF; m^{-1}) can be used to derive an average air concentration AA (μCi m^{-3}) = $C_{gs} \times RF$. An individual located in that area is subjected to a flux density of airborne particles given by $AA \times V_D$ (μCi m^{-2} s^{-1}), where V_D is a velocity (m s^{-1}), either the deposition velocity of particles or the speed that an individual moves relative to the surrounding air.[10] Of all airborne particles that impact the body, only a fraction will be retained on skin. This fraction is described by an interception and retention fraction, r, similar to that developed for descending fallout.

As in the model for an acute deposition onto skin by a fallout event described in Section 3.2, contamination of skin by deposition of resuspended material is assumed to start at time T_0 after a detonation. In resuspension scenarios, the time T_0 often is not the same as the time after detonation when fallout was deposited on the ground. Deposition then continues for a period ΔT_{dep} and ceases at time T_{dep}. After deposition ceases, skin is assumed to remain contaminated for a post-deposition period ΔT_{post} until decontamination occurs (most likely by showering). Skin thus is assumed to be irradiated continuously over a period $\Delta T_{ex} = \Delta T_{dep} + \Delta T_{post}$, during which the dose rate can vary with time.

While showering, a fraction of the radioactive material deposited on skin is removed by washing and exfoliation of skin cells. After showering, the activity of material remaining on skin continues to be reduced by radioactive decay. In this section, we account only for doses to skin that are received up to the time of the first shower. Doses from contamination that remains on skin after the first and any subsequent showers are taken into account using a model described

[10] The units of length (m) and time (s) in these formulations are based on the considerations that resuspension factors generally are given in m^{-1} and that deposition velocities would be given in m s^{-1} in a compatible system of units.

in Section 3.5, and recommended values of parameters to be used in implementing the model for inefficient showering are provided in Sections 4.7.1 and 4.7.2.

Models developed in the following two sections to estimate doses received during the period of a continuous deposition onto skin and after deposition ceases to the time of the first shower represent doses from a single day's exposure to resuspended material. Doses from multiple days of exposure to resuspended material are obtained by summing the doses from each day's exposure. All parameters in the models to estimate doses from resuspended material are discussed in Section 4 except the duration of exposure characterized by ΔT_{dep} and ΔT_{post}, which are specified by the analyst according to a defined exposure scenario.

3.3.2.1 *Dose from Single Radionuclide*

In cases of continuous resuspension and deposition onto skin, the rate of change of the activity concentration of a single radionuclide on skin, C_{skin} (μCi cm^{-2}), at time t is given by the rate at which the concentration on skin increases due to deposition minus the rate at which the concentration decreases due to radioactive decay, assuming no other losses from skin:

$$\frac{\mathrm{d}C_{skin}(t)}{\mathrm{d}t} = \left[0.36 \cdot C_{gs}^{0} \cdot e^{-\lambda_R (t-T_0)} \cdot RF \cdot V_D \cdot AR_f\right] - \left[\lambda_R \cdot C_{skin}(t)\right], \quad t \geq T_0 \tag{3-8}$$

where

- C_{gs}^{0} = activity concentration of radionuclide on ground surface at time T_0 (μCi m^{-2});
- λ_R = radioactive decay constant (h^{-1});
- RF = resuspension factor (m^{-1});
- V_D = deposition velocity of particles onto skin (m s^{-1});
- AR_f = effective interception and retention fraction (unitless); and
- t = time after detonation (h).

The constant 0.36 is a units conversion factor that includes a conversion of the units of deposition velocity to m h^{-1} to be consistent with the units of time (h) and the radioactive decay constant (h^{-1}) and a conversion of the unit of area on the ground surface in m^2 to the unit of area on skin in cm^2 to give an activity concentration on skin, C_{skin}, in μCi cm^{-2}.

The model in eq. (3-8) is based on the following assumptions: (1) the activity concentration of radionuclides in fallout that is intercepted and retained on skin is a function of the activity concentration on the ground surface, which decreases with time only by radioactive decay (i.e., no significant loss of radionuclides from the ground surface occurs by leaching or other processes during the exposure period); (2) the resuspension factor is constant during the time deposition onto skin occurs; (3) deposition onto skin occurs at a sufficiently low rate that the concentration of fallout particles on skin does not saturate during the deposition period; and (4) the effect of weathering of radioactive material from skin is incorporated in values of the interception and retention fraction r, which are based on measured accumulations on skin in the volcanic ash studies under conditions of chronic deposition over several hours (Section 2.2.1), and, thus, the rate of reduction of the activity concentration of radionuclides on skin is determined by the radioactive decay constant.

Equation (3-8) can be solved by using the initial condition that $C_{skin} = 0$ at the beginning of a deposition onto skin at time $t = T_0$. The result is:

$$C_{skin}(t) = 0.36 \cdot C_{gs}^{0} \cdot RF \cdot V_D \cdot AR_f \cdot \left(t - T_0\right) \cdot e^{-\lambda_R (t-T_0)}\ , \quad t \geq T_0 \tag{3-9}$$

The dose rate (rem h^{-1}) during the period of deposition then is given by:

$$\dot{D}(t) = \left[0.36 \cdot C_{gs}^{0} \cdot RF \cdot V_D \cdot AR_f \cdot \left(t - T_0\right) \cdot e^{-\lambda_R (t-T_0)}\right] DRF_{skin}\ , \quad t \geq T_0 \tag{3-10}$$

The total dose (rem) during the period of deposition onto skin (ΔT_{dep}), denoted by D_{dep}, is:

$$\begin{aligned} D_{dep} &= \int_{T_0}^{T_{dep}} \dot{D}(t)\, \mathrm{d}t \\ &= 0.36 \cdot C_{gs}^{0} \cdot RF \cdot V_D \cdot AR_f \cdot DRF_{skin} \cdot \frac{\left[1 - \left(1 + \lambda_R \Delta T_{dep}\right) \cdot \mathrm{e}^{-\lambda_R \Delta T_{dep}}\right]}{\lambda_R{}^2} \end{aligned} \tag{3-11}$$

After deposition ceases, radionuclides are assumed to remain on skin until the first shower, except for removal by radioactive decay, for an additional period ΔT_{post}. By using eqs. (3-9) and (3-10), the dose rate at time t after deposition ceases is given by:

$$\dot{D}(t) = \left[0.36 \cdot C_{gs}^{0} \cdot RF \cdot V_D \cdot AR_f \cdot \Delta T_{dep} \cdot e^{-\lambda_R \Delta T_{dep}}\right] e^{-\lambda_R (t-T_{dep})} \cdot DRF_{skin}\ , \quad t \geq T_{dep} \tag{3-12}$$

The dose delivered to skin during the post-deposition period, denoted by D_{post}, then is:

$$D_{post} = \left[0.36 \cdot C_{gs}^{0} \cdot RF \cdot V_D \cdot AR_f \cdot \Delta T_{dep} \cdot e^{-\lambda_R \Delta T_{dep}}\right] \cdot \frac{1 - e^{-\lambda_R \Delta T_{post}}}{\lambda_R} \cdot DRF_{skin} \qquad (3\text{-}13)$$

Again, the activity concentration of radionuclides on the ground surface, C_{gs}^{0}, in these equations is assumed to be given in units of µCi m^{-2}, the resuspension factor, RF, in m^{-1}, the deposition velocity, V_D, in m s^{-1}, all times in h, the radioactive decay constant, λ_R, in h^{-1}, and the dose-rate factor, DRF_{skin}, in rem h^{-1} per µCi cm^{-2}; the constant 0.36 is a units conversion factor.

The total dose (before showering) is the sum of the dose during the period of deposition on skin (D_{dep}) given by eq. (3-11) and the dose after deposition on skin ceased (D_{post}) given by eq. (3-13). The dose D_{post} is very small if showering occurs immediately after deposition ceases. For exposure to a single radionuclide, doses D_{dep} and D_{post} depend on differences in time ΔT_{dep} and ΔT_{post}, but do not depend on T_0 for given values of ΔT_{dep} and ΔT_{post}. The total dose (before showering) can be increased as described in Section 3.5 to account for the dose received after the first and subsequent showers if showering does not remove all radioactive material on skin.

The equations given above apply to radionuclides for which radioactive decay is important during the period of exposure to resuspended material (about 24 hours or less for exposure on a single day). Such radionuclides are present in the environment only at times shortly after an initial deposition of fallout.

For long-lived radionuclides ($T_{1/2} >> 24$ h), the equations given above can be applied by setting λ_R to zero. Thus, for long-lived radionuclides, the activity concentration on skin at time t during a deposition event is:

$$C_{skin}(t) = 0.36 \cdot C_{gs}^{0} \cdot RF \cdot V_D \cdot AR_f \cdot \left(t - T_0\right), \quad t \geq T_0 \qquad (3\text{-}14)$$

and the total dose during the deposition event is:

$$D_{dep} = 0.36 \cdot C_{gs}^{0} \cdot RF \cdot V_D \cdot AR_f \cdot DRF_{skin} \cdot \frac{\left(\Delta T_{dep}\right)^2}{2} \qquad (3\text{-}15)$$

The dose delivered by a long-lived radionuclide after deposition ceases is the product of the dose rate at the time deposition ceases and the post-deposition exposure time:

$$D_{post} = (0.36 \cdot C_{gs}^{0} \cdot RF \cdot V_D \cdot AR_f \cdot \Delta T_{dep}) \cdot \Delta T_{post} \cdot DRF_{skin} \qquad (3\text{-}16)$$

Again, the total dose (before showering) is the sum of the doses in eqs. (3-15) and (3-16), and this dose can be increased to account for the inefficiency of showering in removing radioactive material from skin using a model described in Section 3.5.

3.3.2.2 *Dose from All Radionuclides Combined*

In modeling the dose from exposure to a mixture of radionuclides in fallout in a resuspension scenario, we again assume, as in the model for descending fallout in Section 3.2.2, that the total activity concentration decreases with time as t^{-x}. The rate of change of the total activity concentration on the ground surface or on skin due only to radioactive decay then can be expressed as $\mathrm{d}C/\mathrm{d}t \sim -x \cdot t^{-1} \cdot C$.

The rate of change of the activity concentration on skin again is given by the rate of increase due to deposition onto skin minus the rate of decrease due to radioactive decay, assuming no other losses from skin. However, in contrast to the case of a single radionuclide, for which the radioactive decay constant λ_R is time-invariant, the fractional rate of change in activity concentration varies with time as $x \cdot t^{-1}$. Thus, during the period ΔT_{dep} when deposition onto skin occurs, the rate of change of the activity concentration on skin is:

$$\frac{\mathrm{d}C_{skin}(t)}{\mathrm{d}t} = \left[0.36 \cdot C_{gs}^{0} \cdot T_0^{+x} \cdot t^{-x} \cdot RF \cdot V_D \cdot AR_f \right] - \left[x \cdot t^{-1} \cdot C_{skin}(t) \right], \quad T_0 \le t \le T_{dep} \qquad (3\text{-}17)$$

where C_{gs}^{0} is the total activity concentration of all radionuclides on the ground (µCi m^{-2}) at time T_0 after a detonation, which can be estimated as indicated in eq. (3-7). Except for the effect of radioactive decay, this model incorporates the same assumptions as the model for the dose from a single radionuclide in eq. (3-8).

By again assuming that the activity concentration on skin at the beginning of the deposition event is zero [$C_{skin}(t=T_0) = 0$], eq. (3-17) can be solved to obtain the activity concentration on skin (µCi cm^{-2}) at any time t during deposition of resuspended material:

$$C_{skin}(t) = 0.36 \cdot C_{gs}^{0} \cdot T_0^{+x} \cdot RF \cdot V_D \cdot AR_f \cdot \left(t^{-(x-1)} - t^{-x} \cdot T_0 \right), \quad T_0 \le t \le T_{dep} \qquad (3\text{-}18)$$

The dose to skin during the period of deposition (ΔT_{dep}) is given by:

$$D_{dep} = \int_{T_0}^{T_{dep}} \dot{D}(t)\,\mathrm{d}t = \int_{T_0}^{T_{dep}} \left[0.36 \cdot C_{gs}^{0} \cdot T_0^{+x} \cdot RF \cdot V_D \cdot AR_f \cdot \left(t^{-(x-1)} - t^{-x} \cdot T_0 \right) \cdot DRF_{skin} \right] \mathrm{d}t$$
$$= \frac{0.36 \cdot C_{gs}^{0} \cdot T_0^{+x} \cdot RF \cdot V_D \cdot AR_f \cdot DRF_{skin}}{(x-1)(2-x)} \left[(x-1) \cdot T_{dep}^{-(x-2)} + (2-x) \cdot T_0 \cdot T_{dep}^{-(x-1)} - T_0^{-(x-2)} \right] \quad (3\text{-}19)$$

After deposition ceases, the activity concentration on skin decreases as t^{-x}:

$$C_{skin}(t) = K \cdot t^{-x} \quad (3\text{-}20)$$

where K is a constant. Since the activity concentration on skin must be a continuous function of time, the concentration at the time deposition ceases obtained from eq. (3-18) is the same as the concentration at that time obtained from eq. (3-20):

$$C_{skin}(T_{dep}) = 0.36 \cdot C_{gs}^{0} \cdot T_0^{+x} \cdot RF \cdot V_D \cdot AR_f \cdot \left(T_{dep}^{-(x-1)} - T_{dep}^{-x} \cdot T_0 \right) = K \cdot T_{dep}^{-x} \quad (3\text{-}21)$$

Solving for the constant K gives:

$$K = 0.36 \cdot C_{gs}^{0} \cdot T_0^{+x} \cdot RF \cdot V_D \cdot AR_f \cdot \left(T_{dep} - T_0 \right) \quad (3\text{-}22)$$

Thus, the activity concentration on skin at any time t after deposition ceases is given by:

$$C_{skin}(t) = 0.36 \cdot C_{gs}^{0} \cdot T_0^{+x} \cdot RF \cdot V_D \cdot AR_f \cdot \left(T_{dep} - T_0 \right) \cdot t^{-x}\,, \quad t \geq T_{dep} \quad (3\text{-}23)$$

After deposition ceases, skin is irradiated continuously to time $T_{ex} = T_{dep} + \Delta T_{post}$. During the post-deposition period ΔT_{post}, the dose to skin is given by:

$$D_{post} = \int_{T_{dep}}^{T_{ex}} K \cdot t^{-x} \cdot DRF_{skin}\ \mathrm{d}t \quad (3\text{-}24)$$

Using the expression for the constant K in eq. (3-22), the result is:

$$D_{post} = \frac{0.36 \cdot C_{gs}^{0} \cdot T_0^{+x} \cdot RF \cdot V_D \cdot AR_f \cdot DRF_{skin}}{(x-1)} \times$$
$$(T_{dep} - T_0) \cdot \left(T_{dep}^{-(x-1)} - T_{\mathrm{ex}}^{-(x-1)} \right), \quad T_{dep} \leq t \leq T_{ex} \quad (3\text{-}25)$$

As noted previously, D_{post} is very small if showering occurs immediately after deposition onto skin ceases.

The dose from the time deposition ceases to the time of the first shower in eq. (3-25) also can be expressed in terms of the activity concentration of radionuclides on skin at the time

deposition ceases, $C_{skin}(T_{dep})$. Using eq. (3-23) at time T_{dep}, the dose during the post-deposition period becomes:

$$D_{post} = C_{skin}\left(T_{dep}\right) \cdot T_{dep}^{+x} \cdot DRF_{skin} \cdot \frac{\left(T_{dep}^{-(x-1)} - T_{ex}^{-(x-1)}\right)}{(\mathrm{x}-1)}, \quad T_{dep} \le t \le T_{ex} \qquad (3\text{-}26)$$

Equation (3-26) is similar to eq. (3-6), which gives the dose due to an *acute* deposition from the time of contamination to the time of the first shower. In the case of a chronic deposition that ceases at time T_{dep}, the dose from time T_{dep} to the time of the first shower (D_{post}) is the same as the dose during the same period from an acute deposition at time T_{dep} that results in an activity concentration on skin equal to the concentration at the time the chronic deposition ceases.

The total dose delivered before the time of the first shower is the sum of the dose during deposition [D_{dep}, eq. (3-19)] and the dose after deposition ceases [D_{post}, eq. (3-25)]:

$$D = \frac{0.36 \cdot C_{gs}^{0} \cdot T_{0}^{+x} \cdot RF \cdot V_D \cdot AR_f \cdot DRF_{skin}}{(x-1)(2-x)} \times \left[T_{dep}^{-(x-2)} - (2-x)\left(T_{dep} - T_0\right) \cdot T_{ex}^{-(x-1)} - T_0^{-(x-2)}\right] \qquad (3\text{-}27)$$

Equation (3-27) was derived using a differential-equation approach. As shown in Appendix B, the same result can be derived using an integral-equation approach. In contrast to the case of exposure to a single radionuclide, doses D_{dep} and D_{post} depend on the time after detonation, T_0, for any period of deposition onto skin (ΔT_{dep}) and post-deposition period (ΔT_{post}).

When showering does not remove all contamination from skin, an additional dose is delivered after the first and subsequent showers. This additional dose is estimated using a model described in Section 3.5.

The total dose in eq. (3-27) is the dose from deposition of resuspended material onto skin during a single day. The dose from multiple days of exposure to resuspended material is obtained by summing the doses from each day's exposure. In Section 3.5, we show how this summation can be performed while accounting for inefficient showering.

3.3.3 Wind-Driven Resuspension

Estimation of downwind airborne concentrations of material resuspended from the ground surface by winds is difficult and generally must rely on a resuspension rate, rather than a resuspension factor (Sehmel 1984). However, if an individual is located in a sufficiently large area that is contaminated at nearly constant levels, a resuspension factor can be used to estimate doses to skin from dermal contamination.

A resuspension factor can be used to derive an average activity concentration in air AA (μCi m^{-3}) due to wind-driven resuspension. When the source is large and uniformly contaminated, the concentration in air is essentially constant over a large area. If an individual is standing on the ground and air is moving toward him with a wind speed V_W (m s^{-1}), the individual is subjected to a flux density of particles $AA \times V_W$ (μCi m^{-2} s^{-1}). This flux density is analogous to a deposition rate per unit area onto a horizontal surface, with the deposition velocity replaced by the wind speed.

On the basis of the analogy between a deposition velocity and wind speed, equations developed in Section 3.3.2 can be applied to wind-driven resuspension by replacing the deposition velocity V_D by the wind speed V_W. As in modeling deposition of airborne material that was resuspended by human activities, wind-driven resuspension results in a continuous deposition onto skin during the time an individual is outdoors in an area open to winds. All assumptions described following eq. (3-8) (Section 3.3.2.1) are assumed to apply to wind-driven resuspension. The relevant equations to estimate dose from deposition onto skin during a single day's exposure to resuspended material are reiterated as follows:

- Dose from single radionuclide during period of deposition onto skin – eq. (3-11);
- Dose from single radionuclide during period from time deposition onto skin ceases to time of first shower – eq. (3-13);
- Dose from all radionuclides in fallout combined during period of deposition onto skin – eq. (3-19);
- Dose from all radionuclides in fallout combined during period from time deposition onto skin ceases to time of first shower – eq. (3-25) or (3-26);

- Total dose from all radionuclides in fallout combined from time deposition onto skin begins to time of first shower – eq. (3-27).

Again, the dose from multiple days of exposure to resuspended material is obtained by summing the doses from each day's exposure.

In some scenarios involving wind-driven resuspension (e.g., exposure of military personnel on residence islands in the Pacific), deposition onto skin occurred over a period of weeks or months. During such long exposures, the resuspension factor (*RF*) often is assumed to decrease with time after an initial deposition on the ground surface. In Section 3.5.4, where the effect of inefficient showering on doses to skin in cases of multiple days of deposition onto skin is discussed, we show how a time-dependence of the resuspension factor can be taken into account in estimating the dose from multiple days of exposure.

In some cases of exposure to fallout that was resuspended by winds (e.g., on residence islands in the Pacific), radionuclide concentrations on the ground surface at times of exposure may have resulted from two or more previous depositions of fallout that occurred at different times. If two or more previous fallout depositions contribute significantly to the total activity concentration of radionuclides on the ground at the time exposure to resuspended material occurred, doses to skin should be calculated by applying the model equations to each of the previous fallout depositions separately and adding the doses to skin from each deposition. It would not be correct to apply the model equations to the total activity concentration of radionuclides on the ground at the time exposure begins, essentially because the time T_0 after detonation when exposure begins would be different for each contributing fallout deposition.

Although Sections 3.3.2 and 3.3.3 discuss resuspension by human activities and by winds separately, this distinction is largely artificial. As indicated by model equations in the two cases, deposition onto skin during a given period of exposure is proportional to a deposition velocity, without regard for whether deposition occurs as a result of gravitational settling, in which case the deposition velocity is denoted by V_D, impaction due to winds, in which case the deposition velocity is the same as the wind speed, V_W, or any combination of processes. In any resuspension scenario, the required quantity is an estimate of the flux density of material impacting the body surface (i.e., amount of material deposited and retained per unit area per unit time) divided by the concentration in air.

3.3.4 Resuspension by Nuclear Detonations

Resuspension of old fallout by the thermal pulse or blast wave produced in a nuclear weapon detonation (Kocher et al. 2009) is an acute event. In estimating doses from dermal contamination due to redeposition of resuspended material, the particle-size distribution of activity in old fallout that was resuspended by a nuclear detonation is assumed to be the same as the particle-size distribution of activity in old fallout on the ground surface. A distinction then is made between redeposition of larger particles of diameter greater than about 100 μm, which should occur within a few tens of minutes in the thermal-pulse region closest to ground zero and within a few minutes in the blast-wave region beyond the thermal-pulse region, and redeposition of smaller particles, which could occur over a period of several hours in the thermal-pulse region and a few hours in the blast-wave region (Kocher et al. 2009). Only forward observers who were located in the blast-wave region at the time of a detonation would be contaminated by redeposition of larger particles, whereas both forward observers and maneuver troops who entered the blast-wave or thermal-pulse region at some time after a detonation would be contaminated by redeposition of smaller particles. Contamination due to redeposition of larger particles should not occur in the thermal-pulse region, given that maneuver troops would not have entered that region until some time after larger particles were redeposited.

We first consider contamination of forward observers due to redeposition of larger particles that were resuspended by the blast wave in a nuclear detonation. As noted above, this exposure occurred within a few minutes. Data reviewed by Kocher et al. (2009) indicate that larger particles in old fallout at NTS carried more than 90% of the resuspended activity; the median estimate of this fraction is 99%. Therefore, in estimating contamination of forward observers due to redeposition of larger particles, it is a good approximation to assume that larger particles carried essentially all the activity of resuspended material. Under that condition, doses to skin of forward observers due to exposure to larger particles in old fallout that was resuspended by the blast wave can be estimated in a manner similar to doses due to descending fallout, and the dose rate at the time of detonation (t) can be estimated as:

$$\dot{D}(t) = f_R \cdot C_{gs}(t) \cdot AR_f \cdot DRF_{skin} \tag{3-28}$$

This equation is the same as eq. (3-2) except it contains an additional parameter (f_R; unitless), which is the fraction of the activity in old fallout on the ground surface that is resuspended by a detonation and redeposited on the ground surface at essentially the same time. In eq. (3-28), the activity concentration on the ground surface, C_{gs}, is the concentration of old fallout at the time of a detonation, not the concentration of any fallout from that detonation that might occur in the same area, and the effective interception and retention fraction, AR_f, is a value that applies to larger particles with a median diameter greater than about 100 μm.

In applying eq. (3-28) to contamination of forward observers due to redeposition of larger particles, the fraction of the activity of radionuclides on the ground surface that is resuspended by the blast wave (f_R) can be estimated using a resuspension factor, RF:

$$RF = \frac{C_{air}}{C_{gs}} \tag{3-29}$$

When resuspended radionuclides are redeposited onto the ground, they produce an activity per unit area (C_R) on the ground surface. If resuspended radionuclides are assumed to be uniformly distributed in a layer of air of height H above ground, the following relationships are obtained:

$$C_R = C_{air} \cdot H = C_{gs} \cdot (RF \cdot H) = C_{gs} \cdot f_R \tag{3-30}$$

$$f_R = RF \cdot H \tag{3-31}$$

Thus, the parameter f_R in eq. (3-28) is estimated as the product of the resuspension factor that applies to all old fallout on the ground surface and the height of the cloud of resuspended material in the blast-wave region.

During an assumed period of exposure after larger particles are redeposited, when only smaller particles would remain in air, dermal contamination of forward observers or maneuver troops in the blast-wave or thermal-pulse regions can be estimated using the equations that apply to resuspension by human activities in Section 3.3.2 and an assumed deposition velocity, V_D (or wind speed, V_W). The resuspension factor (RF) for smaller particles in resuspended fallout is the product of the resuspension factor that applies to the entire amount of old fallout [i.e., the value used to obtain the parameter f_R in eq. (3-31) to estimate contamination of forward observers due to redeposition of larger particles in the blast-wave region or a higher value in the thermal-pulse region] and an assumed fraction of the activity in old fallout that was carried by smaller particles.

In applying equations in Section 3.3.2, the effective interception and retention fraction, AR_f, is a value that applies to smaller particles with a median diameter less than about 100 μm.

An additional parameter that could be included in eq. (3-28) and in the model that uses a deposition velocity to estimate contamination due to redeposition of smaller particles is a dispersion factor, f_D. This parameter would take into account that old fallout that was resuspended by a nuclear detonation may be spread over a larger area around ground zero, due to the outward-directed winds associated with a blast wave (Glasstone and Dolan 1977), than the area of old fallout prior to resuspension. This dispersion would result in a dilution of the concentration in air that is estimated using a resuspension factor. The dispersion factor, f_D, can be estimated by assuming that a detonation resuspended material over the area of a circle of radius R_1 and dispersed that material over the area of a circle of larger radius R_2. For example, if the initial concentration of radionuclides on the ground is essentially uniform and resuspended material is assumed to be dispersed uniformly by a detonation, the dispersion factor is given by the ratio of the areas of the two circles. This dispersion factor accounts for horizontal dispersion of resuspended material. Vertical dispersion also occurs and is taken into account in the parameter f_R, which is calculated using eq. (3-31).

We expect that the dispersion factor, f_D, generally should be small, i.e., less than a factor of two. A dispersion factor of two would mean that the radius of the cloud of resuspended material would be about 40% larger than the radius of the source region. Such a large increase seems extreme, especially at the outer boundary of the blast-wave region. Given that the uncertainty in a resuspension factor in the thermal-pulse and blast-wave regions is much larger than any credible value of the dispersion factor, we believe that it would be reasonable to ignore this parameter in most dose reconstructions for forward observers or maneuver troops.

3.4 Contamination of Skin from Other Activities

Accumulation of soil particles on skin also can occur as result of direct contact with soil or contaminated equipment while performing various activities. Studies of levels of accumulation of soil on skin while performing various common activities are summarized in Appendix A, Tables A-1 and A-2, and measured accumulations of soil on skin and clothing of troops while crawling under simulated combat conditions are summarized in Appendix A,

Tables A-3 and A-4. As discussed in Section 2.1, more accumulation occurs in regions of the body where soil touches the skin, and accumulation is increased by the presence of moisture.

Sheppard and Evenden (1994) observed soil loadings on skin from direct contact with soil of 2 to 6 mg_{soil} per cm^2_{skin} when soil was moist. At soil loadings of 2 mg_{soil} per cm^2_{skin} or more, dirt is visible on skin, and it is likely that cleaning will take place sooner than when dirt is not easily visible. For all activities listed in Tables A-1 and A-2 except children playing in mud, the dermal soil loading was less than 1 mg_{soil} per cm^2_{skin}. The largest accumulations of soil occurred on the skin of gardeners, farmers, and earth-scraping machine operators, all of whom perform operations that involve moving or handling dirt.

Some military personnel performed similar activities, such as digging trenches, and other activities as well (e.g., handling contaminated equipment). To estimate doses to skin from dermal contamination during these activities, care should be taken in accounting for the type of activity, especially in assessing whether soil that was handled was contaminated. For example, digging a trench in a fallout field involved lots of dirt moving, but most of the dirt that was located well below the ground surface was uncontaminated.

Once a soil loading on skin is estimated, the activity concentration of radionuclides on skin can be calculated using an estimate of the specific activity ($\mu Ci\ g^{-1}$) of the accumulated material. Doses to skin then can be calculated using dose-rate factors for all radionuclides in fallout combined discussed in Section 4.6 or dose-rate factors for individual radionuclides, such as those reported by Kocher and Eckerman (1987).

Another potential exposure pathway is dermal contamination by transfer of radioactive particles due to contact with a contaminated surface (contact transfer). This pathway is potentially important, for example, for military personnel who maintained, repaired or decontaminated aircraft or ships. Contact transfer results in direct contamination of hands and perhaps other regions of the body (e.g., forearms, shoulders, legs). Contact transfer also can result in indirect contamination by transfer of radioactive material from hands to other regions of the body (e.g., contamination of the face when touched by a contaminated hand).

Contact transfer was studied by Fogh et al. (1999) using surfaces that were uniformly contaminated with stable tracers that can be activated by neutrons. Tracers were attached to small particles with median diameters of 5 or 10 μm, and surfaces were touched by a gloved

hand for 30 seconds. Gloves made of textured latex, which was considered to be a good representation of the surface of human skin, were used to eliminate concerns about uncertainties in the efficiency of recovery of particles from bare skin. Dry gloves picked up about 20% of the particles of either diameter (standard deviation about 11%) from such surfaces as cotton, paper, wood, or plastic. The efficiency of contact transfer increased to about 30% (standard deviation about 16%) when damp gloves were used.

In another study, Brouwer et al. (1999) estimated a contact transfer efficiency of less than 2% for fluorescent-dyed particles on surfaces with relatively low loadings of 10 to 200 μg cm^{-2}. The average loading on skin in that study thus was on the order of 1 μg cm^{-2}.

The types of studies described above could be useful in estimating dermal contamination of hands and other body surfaces by direct contact if a reasonable estimate of the activity concentration on a contaminated surface or object can be obtained. If an activity concentration on skin is estimated using such contact transfer efficiencies, doses to skin can be estimated using models that apply to an acute deposition on skin presented in Section 3.2, with the effect of inefficient showering taken into account using models presented in the following section.

3.5 Effect of Inefficient Showering

Doses to skin depend on the time that contaminated material stays on or close to the skin surface. Washing reduces but probably does not eliminate all contamination, especially contamination attached to smaller particles that become embedded in pores and creases of skin. When showering is inefficient in removing contamination, the total dose due to a given deposition onto skin is higher than the dose delivered to the time of the first shower.

In previous sections, we developed models to estimate the dose to skin from the time dermal contamination begins until the time of the first shower. The model formulation depends on whether deposition onto skin is treated as an acute event (Section 3.2) or as a continuous occurrence over some period prior to the time of the first shower (Sections 3.3.2 and 3.3.3).

In this section, we present models to estimate the total dose to skin when showering is only partially efficient in removing contamination; these models include contributions to the

dose after the time of the first shower. In presenting models to represent the effects of inefficient showering, we consider three distinct exposure scenarios:

[1] an acute (instantaneous) deposition onto skin before the time of the first shower;

[2] a continuous deposition onto skin that ceases before the time of the first shower;

[3] a chronic (long-term) deposition onto skin that continues after the time of the first shower and for a number of successive days.

In the third scenario, deposition onto skin may occur only during a fraction of the time on each day (e.g., while an individual is outdoors), rather than continuously throughout each day.

Activity concentrations of radionuclides on skin are reduced by two processes while showering: washing (i.e., removal from the surface of skin by water and soap) and exfoliation of skin cells (i.e., normal loss of skin cells due to scrubbing or other abrasions). When showering removes only a fraction of the contamination on skin at that time and the time between showers does not vary greatly, progressively lower doses are delivered after each shower.

3.5.1 Modeling of Removal of Radionuclides from Skin by Exfoliation and Washing

Removal (and renewal) of skin cells is a natural process with a cell turnover time of about 20 days on the upper limbs, 30 days on the lower limbs, 40 days on the abdomen, and 120 days on the scalp (ICRP 1975). While some removal of skin cells occurs between showers, exfoliation probably occurs mainly as result of scrubbing while showering, and it is expected that the loss of skin cells is similar during each shower.

By assuming that an individual would shower once each day, the fraction of the contamination on skin that is removed by exfoliation during each shower, denoted by β, is numerically equal to the reciprocal of the skin cell turnover time in days. The same fraction β is assumed to apply to the activity concentration on skin at the time of each shower (i.e., on each day). Thus, some contamination is assumed to remain on skin after all cells that were present at the time of deposition are removed by exfoliation.

The first shower may remove much of the contamination from skin, but subsequent showers are less efficient (Sharp and Chapman 1957; Friedman 1958; Fogh et al. 1999) as the

remaining contamination becomes more embedded in skin folds and pores. In this report, the fraction of the activity concentration of radionuclides on skin that is removed by washing during each shower is denoted by γ_j, where j counts each shower after a deposition on skin ($j = 1,\ldots,N$).

The fraction of the activity concentration of radionuclides on skin at the time of the jth shower that remains after that shower, taking into account removal by exfoliation of skin cells and washing, is estimated as $\alpha_j = 1 - (\gamma_j + \beta)$. As noted above, the fraction removed by exfoliation, β, is assumed to be the same in all showers. The fraction removed by washing, γ_j, is assumed to decrease or remain constant in each successive shower. Recommended probability distributions of β and γ_j are discussed in Sections 4.7.1 and 4.7.2, respectively.

3.5.2 Effect of Inefficient Showering – Acute Deposition Before First Shower

After an acute dermal contamination event (i.e., an event that is assumed to occur instantaneously) at time T_0 after a detonation, the dose D_1 received from time T_0 to the time of the first shower, T_1, is given by eq. (3-5) in cases of exposure to a single radionuclide and by eq. (3-6) in cases of exposure to a mixture of radionuclides in fallout from a nuclear detonation. The time Δt in those equations is equal to $T_1 - T_0$.

If an individual takes N showers at times $T_1, T_2, \ldots, T_N$, the total dose during the period from T_0 to T_N (i.e., the sum of the dose to the time of the first shower and the dose after the first shower that results from inefficient showering) in cases of contamination by a single radionuclide is given by:

$$D_N = C_{skin}(T_0) \cdot DRF_{skin} \cdot \sum_{j=1}^{N} \left[\frac{e^{-\lambda_R (T_{j-1} - T_0)} - e^{-\lambda_R (T_j - T_0)}}{\lambda_R} \cdot \left(\prod_{k=1}^{j-1} \alpha_k \right) \right] \tag{3-32}$$

As indicated in eq. (3-2) (Section 3.2), the activity concentration of the radionuclide on skin at the time of an acute deposition, $C_{skin}(T_0)$, is estimated as $C_{gs}(T_0) \times AR_f$, where C_{gs} is the activity concentration of the radionuclide deposited on the ground surface and AR_f is the effective interception and retention fraction. In cases of contamination by a mixture of radionuclides in fallout, the total dose from time T_0 to time T_N is given by:

$$D_N = C_{skin}(T_0) \cdot T_0^{+x} \cdot DRF_{skin} \cdot \sum_{j=1}^{N} \left[\frac{T_{j-1}^{-(x-1)} - T_j^{-(x-1)}}{x-1} \cdot \left(\prod_{k=1}^{j-1} \alpha_k \right) \right] \tag{3-33}$$

When $j = 1$ (i.e., at the time of the first shower), the term $\left(\prod_{k=1}^{j-1} \alpha_k \right)$ is equal to 1.0, and doses to the time of the first shower, D_1, obtained from eqs. (3-32) and (3-33) are the same as given in eqs. (3-5) and (3-6), respectively. A derivation of eq. (3-33) is given in Appendix D.1. A similar approach can be used to derive eq. (3-32).

By subtracting the dose delivered to the time of the first shower, T_1, from the total dose in eq. (3-32), the dose delivered after the time of the first shower that results from inefficient showering, denoted by D_{sh}, in cases of exposure to a single radionuclide is given by:

$$D_{sh} = C_{skin}(T_0) \cdot DRF_{skin} \cdot \sum_{j=2}^{N} \left[\frac{e^{-\lambda_R (T_{j-1} - T_0)} - e^{-\lambda_R (T_j - T_0)}}{\lambda_R} \cdot \left(\prod_{k=1}^{j-1} \alpha_k \right) \right] \tag{3-34}$$

Similarly, the dose delivered after the time of the first shower in cases of exposure to a mixture of radionuclides in fallout is given by:

$$D_{sh} = C_{skin}(T_0) \cdot T_0^{+x} \cdot DRF_{skin} \cdot \sum_{j=2}^{N} \left[\frac{T_{j-1}^{-(x-1)} - T_j^{-(x-1)}}{x-1} \cdot \left(\prod_{k=1}^{j-1} \alpha_k \right) \right] \tag{3-35}$$

The time between an acute deposition and the first shower usually would be defined by the assumed scenario. This time may be as little as an hour or less or much as 24 hours if an individual is assumed to shower once each day. After the first shower, the time between showers, $T_j - T_{j-1}$, normally should be 24 hours, but any times between showers can be assumed.

In principle, the dose D_{sh} should be evaluated assuming a large number of showers, N. It usually should be sufficient to set N at no more than 120 days, which is the largest turnover time for skin cells due to exfoliation (ICRP 1975). Doses from contamination that remains on skin after 120 showers should be negligible.

The importance of the dose after the first shower compared with the dose to the time of the first shower depends on the time between an acute deposition onto skin and the first shower ($T_1 - T_0$) and the efficiency of showering (α_j). For example, the total dose is dominated by the dose received before the time of the first shower, regardless of the times when deposition and the

first shower occur, if showering is highly efficient in removing contamination (α is close to zero), but the dose received after the time of the first shower is dominant if the first shower occurs close to the time of deposition and each shower removes only a small fraction of the contamination (α is close to 1.0). The rate of decay of radionuclides deposited on skin also affects this comparison. For given times T_0 and T_1 and values of α_j, the dose after the first shower generally increases as the decay rate decreases, and vice versa.

Sections 4.7.1 and 4.7.2 discuss available data related to efficiencies of showering and the effect of different assumptions about T_0, T_1, and α_j on the importance of the dose received after the time of the first shower compared with the dose to the time of the first shower.

3.5.3 Effect of Inefficient Showering – Continuous Deposition Before First Shower

In Sections 3.3.2 and 3.3.3, models were developed to estimate the dose delivered to the time of the first shower when a continuous deposition of resuspended material onto skin at a constant rate occurs. In this section, we consider the effect of inefficient showering on the total dose when a chronic deposition ceases before the time of the first shower.

As in Section 3.3.2, contamination of skin due to a continuous deposition of resuspended radionuclides is assumed occur for a period ΔT_{dep}, starting at time T_0 after a detonation and ending at time T_{dep}. After deposition ceases, skin is assumed to remain contaminated for an additional post-deposition period ΔT_{post} until the first shower. The dose delivered to the time of the first shower is the sum of the doses during deposition and the post-deposition period. If D_{sh} again denotes the dose received after the time of the first shower (i.e., the additional dose that results from incomplete removal of contamination from skin by showering), the total dose is:

$$D = D_{dep} + D_{post} + D_{sh} \tag{3-36}$$

Equation (3-36) applies in cases of exposure to a single radionuclide or a mixture of radionuclides. The following discussion considers exposure to a mixture of radionuclides in fallout. However, the same approach can be used in cases of exposure to a single radionuclide.

In cases of exposure to a mixture of radionuclides in fallout, doses D_{dep} and D_{post} in eq. (3-36) are calculated using eqs. (3-19) and (3-25), respectively. These doses are unaffected by inefficient showering, since they are delivered before the time of the first shower.

The dose delivered after the first shower, D_{sh}, can be obtained from eq. (3-35), which applies to an acute deposition at time T_0, by substituting the time deposition ceases, T_{dep}, for T_0, because doses at any time after deposition onto skin ceases depend only on the activity concentration of radionuclides on skin at time T_{dep} but do not depend on the time history of deposition onto skin between the time deposition begins, T_0, and the time deposition ceases [see discussion following eq. (3-26) in Section 3.3.2.2]. Thus, D_{sh} in cases of a continuous deposition onto skin that ceases before the time of the first shower can be expressed as:

$$D_{sh} = C_{skin}\left(T_{dep}\right) \cdot T_{dep}^{+x} \cdot DRF_{skin} \cdot \sum_{j=2}^{N} \left[\frac{T_{j-1}^{-(x-1)} - T_{j}^{-(x-1)}}{x-1} \cdot \left(\prod_{k=1}^{j-1} \alpha_k \right) \right] \qquad (3\text{-}37)$$

The model formulation in eq. (3-37) illustrates the importance of the activity concentration on skin at the time deposition ceases. However, eq. (3-37) has a different formulation than the models to estimate doses D_{dep} and D_{post} in eqs. (3-19) and (3-25), respectively. The same model formulations are obtained by expressing the concentration $C_{skin}(T_{dep})$ in eq. (3-37) in terms of its parameters using eq. (3-23) evaluated at time T_{dep}. The dose D_{sh} then is given by:

$$D_{sh} = 0.36 \cdot C_{gs}^{0} \cdot T_0^{+x} \cdot RF \cdot V_D \cdot AR_f \cdot (T_{dep} - T_0) \cdot DRF_{skin} \cdot \sum_{j=2}^{N} \left[\frac{T_{j-1}^{-(x-1)} - T_{j}^{-(x-1)}}{x-1} \cdot \left(\prod_{k=1}^{j-1} \alpha_k \right) \right] \qquad (3\text{-}38)$$

This formulation of the dose delivered after the first shower is more transparent in indicating the parameters used to estimate deposition on skin. It also is more convenient when the concentration on skin at the time deposition ceases, $C_{skin}(T_{dep})$, generally would not be known but would be calculated using eq. (3-23).

Use of the deposition velocity, V_D, in eq. (3-38) indicates that the model applies in scenarios involving resuspension by human activities (Section 3.3.2). However, as discussed in Section 3.3.3, eq. (3-38) also applies in cases of exposure to radionuclides resuspended by winds, in which case the deposition velocity is the same as the wind speed, V_W.

3.5.4 Effect of Inefficient Showering – Deposition Continues After First Shower

This section considers the effect of inefficient showering when a chronic (long-term) deposition of radionuclides onto skin continues after the time of the first shower and for a number of successive days. Such a scenario could occur, for example, when military personnel were stationed on a residence island in the Pacific for a period of days or more and were exposed to fallout resuspended by winds. Resuspension is the only source of long-term deposition onto skin considered explicitly in this report, and wind-driven resuspension at wind speed V_W (m s^{-1}) is assumed in the model equations presented below. Deposition on any given day can be intermittent (e.g., while an individual is outdoors, but not while indoors). In addition, as in the previous section, only the case of exposure to a mixture of radionuclides in fallout is considered.

A long-term chronic exposure is equivalent to a sequence of daily depositions onto skin that take place from a starting day (m = 1) to an ending day (m = M); the timeline of the sequence of daily depositions, including the time deposition begins on each day, the time deposition ceases on each day, and the time of a shower on each day, is depicted in Fig. 3-1. On any given day, the dose from the time deposition begins on that day to the time of the next shower is estimated using the model equations developed in Sections 3.3.2 as applied to wind-driven resuspension by replacing the deposition velocity, V_D, by the wind speed, V_W; in cases of exposure to a mixture of radionuclides in fallout, eq. (3-19) gives the dose during the period of deposition onto skin (D_{dep}), and eq. (3-25) gives the dose from the time deposition ceases to the time of the next shower (D_{post}). The dose after the time of the next shower from that day's deposition onto skin when showering is assumed to be inefficient in removing contamination from skin is estimated using eq. (3-38). The total dose from depositions during all days of exposure is the sum of the doses from each day's deposition.

In a scenario involving resuspension by winds, the resuspension factor (RF) can be considered constant over the course of any given day. However, the resuspension factor is expected to decrease with time after deposition of fallout on the ground surface (Anspaugh et al. 1975, 2002; Garger et al. 1997b).

Various mathematical formulations of the time-dependence of the resuspension factor have been proposed. In the following discussion, the resuspension factor is assumed to decrease

with time in accordance with a power function, similar to the assumed dependence on time of the activity of a mixture of radionuclides in fallout. The resuspension factor is assumed to decrease with time as:

$$RF(t) = RF_0 \cdot T_0^{+y} \cdot t^{-y} \tag{3-39}$$

where RF_0 is the resuspension factor at time T_0 after a detonation when fallout is deposited on the ground surface and t is the time after deposition; the times T_0 and t are in hours.

A power-function representation of the time-dependence of the resuspension factor, as in eq. (3-39), was introduced by Garland (1982) and Garland et al. (1991), who proposed a value of the exponent y of 1, meaning that the resuspension factor was assumed to decrease with time as $1/t$. In modifications of the power-function model that were based on studies of resuspension of fallout from the Chernobyl accident, Garger et al. (1997b) proposed a value y of 1.07, and Nair et al. (1997) proposed values of y of 1 for the first 1,000 days (about 3 years) after deposition and zero at later times (i.e., a constant resuspension factor).

Given the assumption about the time-dependence of the resuspension factor in eq. (3-39) and the equations for the dose from deposition on skin on a given day in the previous section, the total doses during the three time periods of interest from exposure over M days are as follows:

<u>Dose during all periods of deposition onto skin</u> –

$$D_{dep} = 0.36 \cdot V_W \cdot AR_f \cdot DRF_{skin} \times \sum_{m=1}^{M} \left\{ \frac{C_{gs}^{0,m} \cdot T_{0,m}^{+x} \cdot \left(RF_0 \cdot T_{0,1}^{+y} \cdot T_{0,m}^{-y}\right)}{(x-1)(2-x)} \cdot \left[(x-1) \cdot T_{dep,m}^{-(x-2)} + (2-x) \cdot T_{0,m} \cdot T_{dep,m}^{-(x-1)} - T_{0,m}^{-(x-2)}\right] \right\} \tag{3-40}$$

<u>Dose during all periods from time deposition onto skin ceases to time of next shower</u> –

$$D_{post} = 0.36 \cdot V_W \cdot AR_f \cdot DRF_{skin} \times \sum_{m=1}^{M} \left\{ \frac{C_{gs}^{0,m} \cdot T_{0,m}^{+x} \cdot (RF_0 \cdot T_{0,1}^{+y} \cdot T_{0,m}^{-y})}{(x-1)} \cdot \left[T_{dep,m} - T_{0,m}\right] \cdot \left[T_{dep.m}^{-(x-1)} - T_{m}^{-(x-1)}\right] \right\} \tag{3-41}$$

Dose during all periods after time of next shower –

$$D_{sh} = 0.36 \cdot V_W \cdot AR_f \cdot DRF_{skin} \times$$

$$\sum_{m=1}^{M} \left\{ C_{gs}^{0,m} \cdot T_{0,m}^{+x} \cdot \left(RF_0 \cdot T_{0,1}^{+y} \cdot T_{0,m}^{-y} \right) \cdot \left(T_{dep,m} - T_{0,m} \right) \cdot \sum_{j=m+1}^{N} \left[\frac{T_{j-1}^{-(x-1)} - T_j^{-(x-1)}}{x-1} \left(\prod_{k=1}^{j-m} \alpha_k \right) \right] \right\} \quad (3\text{-}42)$$

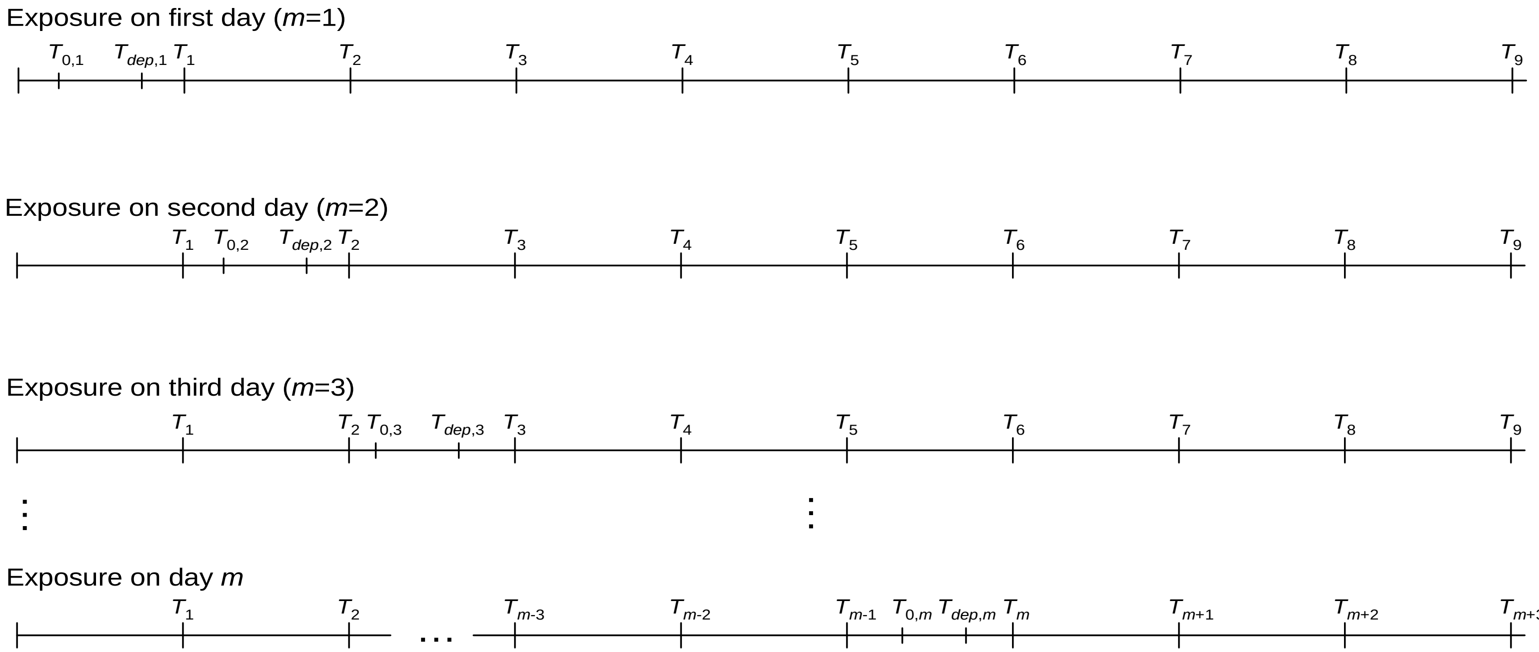
The constant 0.36 again is a units conversion factor that is defined following eq. (3-8) in Section 3.3.2.1. These equations can be applied to periods of exposure when the resuspension factor (*RF*) is considered to be constant by setting the exponent *y* equal to zero.

3.6 Modeling of Doses from Alpha-Emitting Radionuclides

Doses to skin from dermal contamination by radionuclides that emit alpha particles usually are not considered in radiation dose assessments. Neglect of this exposure pathway perhaps has been based on a view that alpha particles emitted by radionuclides are not sufficiently energetic to penetrate the epidermis and irradiate radiosensitive tissues in the basal layer of skin. As indicated by calculations presented in Section 4.6.2, neglect of external exposure to many alpha-emitting radionuclides that might be deposited on the body surface is reasonable if the nominal depth of radiosensitive tissues is taken to be 7 mg cm^{-2}, as is normally the case in radiation protection (ICRP 1977), because ranges of alpha particles emitted by most radionuclides of potential concern are less than that depth.

However, data reported by Whitton (1973) indicate that the average thickness of the epidermis in some regions of the body is about 4 mg cm^{-2}, and that the thickness can be as low as 2 mg cm^{-2} in those regions in some individuals. Such thicknesses are less than ranges of alpha particles emitted by important radionuclides in fallout. An early analysis by Harvey (1971) indicated that the alpha dose rate to skin per unit activity concentration on the body surface could be as high as 10^4 rem h^{-1} per μCi cm^{-2} for such radionuclides as ^{242}Cm in some regions of the body. Since dose-rate factors of that magnitude are much higher than dose-rate factors for beta-emitting radionuclides, which are on the order of 10 rem h^{-1} per μCi cm^{-2} or less (Kocher and Eckerman 1987), alpha doses to skin could be important even though concentrations of alpha emitters in fallout may be much less than concentrations of beta emitters.

Models presented in Section 3 were developed primarily to address doses to skin from beta-emitting radionuclides. However, the same models can be used to estimate doses to skin from alpha-emitting radionuclides deposited on the body surface. The only difference is in values of the dose-rate factor (*DRF*). Appropriate dose-rate factors are discussed in Section 4.6.1 for beta emitters and Section 4.6.2 for alpha emitters.



$T_{0,m}$ = time when deposition on skin begins during given day of exposure; m=1,…,M

$T_{dep,m}$ = time when deposition on skin ends during given day of exposure; m=1,…,M

T_j = time of showering on given day; j=1,…,N

All times are specified in hours after time of detonation

Figure 3-1. Time sequence of occurrences in scenario involving multiple days of deposition onto skin due to wind-driven resuspension followed by long-term exposure of skin resulting from inefficiency of showering in removing contamination.

4. PARAMETERS IN MODELS TO ESTIMATE DOSES TO SKIN FROM DERMAL CONTAMINATION

This section discusses recommended values of parameters in the models developed in Section 3 to estimate doses to skin from dermal contamination. Parameters discussed include the interception and retention fraction, *r*, and its adjustment factors introduced in eq. (3-4), the resuspension factor, the deposition velocity or wind speed, the dose-rate factor and its modifiers, and parameters in the models to account for inefficient showering.

Parameter values discussed in this section are intended to apply in estimating doses to skin from dermal contamination by mixtures of radionuclides in fallout from nuclear detonations. Recommended parameter values are described by probability distributions to represent their uncertainty. A point estimate of each parameter that could be used in deterministic calculations (e.g., calculations to compare doses to skin from dermal contamination and doses from exposure to a contaminated ground surface described in Section 6) also is provided.

4.1 Interception and Retention Fraction

The interception and retention fraction, *r*, is defined as the ratio of the mass of material that is deposited and retained per unit area on skin (mg cm^{-2}) to the time-integrated flux density of material traveling towards the body (mg cm^{-2}). In the case of exposure to descending fallout throughout the period of descent, the time-integrated flux density of material traveling towards the body is equal to the mass of material deposited per unit area on the ground surface.

In this report, we mainly rely on data from the CENIZA-ARENA volcanic ash studies in Costa Rica to estimate interception and retention fractions in various regions of the body under conditions of exposure of military personnel at atmospheric weapons tests. Data obtained from wind-tunnel studies are used to complement and confirm data from the volcanic ash studies. As described in Section 2.2.1, the quantity estimated in the volcanic ash study is a skin contamination factor a_h, which is defined as the ratio of the mass of descending ash that accumulated on a specific portion of an exposed body surface to the mass per unit area that was deposited on the ground surface; this quantity is given in units of cm^2. The interception and

retention fraction then is estimated as the ratio of a_h to the surface area of skin (s) over which a_h was measured [$r = (a_h/s)$; eq. (3-3) in Section 3.2].

Estimation of the interception and retention fraction, r, in different regions of the body is challenged by limitations in available data on the skin contamination factor, a_h. As indicated in Table 2-2, estimates of a_h are available for the forearms, face, forehead, and inside of the ears, but not for the torso, neck, or legs. A reasonable way to use the available data is to estimate the interception and retention fraction for regions of the body for which data are available and apply those estimates to other similar regions for which no data are available. The interception and retention fraction normally should be less than 1.0, given that skin cannot retain a mass of descending material per unit area larger than mass per unit area deposited on the ground surface. However, values of r greater than 1.0 are possible when inadvertent transfer of material from one region of the body (i.e., hand, forearms) to other regions (e.g., face, forehead) occurs. In addition, a larger mass per unit area than on the ground surface can accumulate in special regions of the body, such as the back of the neck under a collar, around the waist under a belt, on the shin area around the edge of a boot, or behind the ears. In these regions, a relatively small area of skin can accumulate particles that impact a larger area of the body. For example, particles that impact the back of the head may migrate and accumulate on skin under a collar.

The following sections describe the probability distributions of interception and retention fractions, r, that are assumed to apply in various regions of the body. All assumed probability distributions are summarized in Table 4-1.

4.1.1 Interception and Retention Fraction for Hair on Scalp

Measurements of the skin contamination factor, a_h, for hair on the scalp are summarized in Table 2-2 and Fig. 2.1. Five distinct measurements for a male with a crew-cut hairstyle ranged from 10 to 585 cm^2. These measurements can be represented by a lognormal distribution with a GM of 182 cm^2 and GSD of 2.80. For a male with medium cut hair, six distinct measurements of a_h ranged from 48 to 620 cm^2 and can be represented by a lognormal distribution with a GM of 163 cm^2 and GSD of 2.56. When all distinct measurements on all subjects are pooled, a_h can be represented by a lognormal probability distribution with a GM of 164 cm^2 and GSD of 2.45.

For males, estimates of the surface area of the head have a mean of 1180 cm^2 and standard deviation of 160 cm^2 (Appendix A, Table A-6). These data can be represented by a lognormal probability distribution with a GM of 1169 cm^2 and GSD of 1.14. If we assume that the surface area of the scalp is about 60% of the surface area of the head and represent this uncertain fraction by a uniform probability distribution with a minimum at 0.5 and maximum at 0.7, the surface area of the scalp can be represented by a lognormal probability distribution with a GM of 700 cm^2 and GSD of 1.14.

By combining the skin contamination factor for all subjects and the surface area of the scalp described above, the resulting interception and retention fraction $r = (a_h/s)$ can be represented by a lognormal probability distribution with a GM of 0.23 and GSD of 2.45; the 90% credibility interval (CI) of this distribution is (0.053, 1.0). This probability distribution has about 5% of its values greater than 1.0. Given that it is possible for material that accumulates on hands to be transferred to hair by running of fingers through hair, which is a common habit, this probability distribution is considered acceptable for estimating doses to skin of the scalp.

The skin contamination factor, a_h, for hair on the scalp should be positively correlated with the surface area of the head, s, given that a greater surface area increases the mass of descending ash that impacted that area; the same type of correlation should occur in other regions of the body. However, this correlation has a negligible effect on the uncertainty in the interception and retention fraction, $r = a_h/s$, when the uncertainty in a_h is much greater than the uncertainty in s, which is generally the case. This correlation is ignored in developing probability distributions of interception and retention fractions in any region of the body.

4.1.2 Interception and Retention Fraction for Skin of Forearms

As indicated in Table 2-2, only three measurements of the skin contamination factor, a_h, for the forearms were obtained in the volcanic ash studies (135, 66, and 172 cm^2). The last two values (66 and 172 cm^2) represent the amount of ash collected from forearms and hands. The geometric mean of the three measurements of a_h is 115 cm^2.

Estimates of the surface area of skin on the forearms in males have a mean of 1140 cm^2 and standard deviation of 127 cm^2 (Appendix A, Table A-6). These data can be represented by a

lognormal probability distribution with a GM of 1133 cm^2 and GSD of 1.12. Similarly, estimates of the surface area of skin on the hands, which have a mean of 840 cm^2 and standard deviation of 127 cm^2, can be represented by a lognormal probability distribution with a GM of 831 cm^2 and GSD of 1.16. By adding the two probability distributions, the total surface area of the forearms and hands is assumed to have a GM of 1963 cm^2 and GSD of 1.14.

The three measurements of the skin contamination factor, a_h, for the forearms are insufficient to characterize its variability. Since the forearms and back of the hands often are covered by more abundant hair than the face and can be held in a horizontal position, a GSD of 3.0 can be chosen for a_h, similar to the estimated GSD for medium-cut hair indicated in Fig. 2-1. A lognormal probability distribution with a GM of 115 cm^2 and GSD of 3.0 has a 95th percentile of 700 cm^2, which is reasonably close to the largest measured value of a_h for hair (620 cm^2; Table 2-2). The 5th percentile of a_h is 19 cm^2, which is the same as the larger measured value for the face discussed in the next section. Thus, the assumed lognormal probability distribution of the skin contamination factor, a_h, for the forearms and hands seems reasonable.

Using the skin contamination factor and skin surface area described above, the interception and retention fraction, r, for the forearms is assumed to be lognormally distributed with a GM of 0.06 and GSD of 3.0 [90% CI of (0.01, 0.36)]. This probability distribution has a reasonable 95th percentile, but the probability that r is greater than 1.0 is 0.7%. Thus, when eq. (3-4) is applied to estimate doses to skin of the forearms using Monte Carlo techniques to propagate uncertainty, a condition should be set to limit r to values less than 1.0.

4.1.3 Interception and Retention Fraction for Skin of Face

As indicated in Table 2-2, only two measurements of the skin contamination factor, a_h, for the face were obtained in the volcanic ash studies (2.5 and 19 cm^2). In the absence of more detailed information, we assume that a best estimate of the skin contamination factor for the face is the geometric mean of the two measured values, or 7 cm^2.

The two measurements given above are insufficient to determine the variability in the skin contamination factor, a_h, for the face. A greater number of measurements of a_h is available for hair. As discussed in the previous section, the variability in a_h for hair can be represented by

a lognormal probability distribution with a GSD of either 2.80 for a male with a crew-cut hairstyle or 2.56 for a male with medium-cut hairstyle, and a GSD of 2.45 is obtained when the data from all subjects are pooled.

It is expected that the variability in a_h is larger for the face than for hair, in part because facial hair may or may not be present at the time of deposition. During the course of a day, facial hair on males can change from non-existent immediately after shaving to short rough growth (stubble) at the end of the day. This is potentially important when, on average and as indicated in Table 4-1, the interception and retention fraction for forearms, which are typically covered with some hair, is a factor of four greater than the interception and retention fraction for the face. This comparison indicates that the presence or absence of facial hair may add a variation of as much as a factor of four in the interception and retention fraction, which is equivalent to an uncertainty factor that can be represented by a GM of 1.0 and GSD of 2.3.

If the GSD that represents the variability of data for hair is combined with the GSD of 2.3 that accounts for the variability due to the presence or absence of facial hair (e.g., in quadrature or by Monte Carlo methods), a possible GSD of an uncertain a_h of about 3.5 is obtained. In this study, we use a lognormal probability distribution with a GM of 7 cm^2 and GSD of 3.5 to represent the uncertainty in the skin contamination factor, a_h, for the face.

For males, data summarized in Appendix A.2 indicate that the surface area of the head has a mean of 1180 cm^2 and standard deviation of 160 cm^2. The variability of the surface area of portions of human skin probably is described by lognormal probability distributions. We represent the uncertainty in the surface area of the head by a lognormal probability distribution with a mean of 1180 cm^2 and standard deviation of 160 cm^2. This distribution has a GM of 1169 cm^2 and GSD of 1.14. If we assume that the surface area of the face is about 40% of the surface area of the head and represent this uncertain fraction by a uniform probability distribution with a minimum at 0.3 and maximum at 0.5, the surface area of the face can be represented by a lognormal probability distribution with a GM of 460 cm^2 and GSD of 1.2.

Using the skin contamination factor and skin surface area for the face described above, the interception and retention fraction, r, for the face was estimated using Monte Carlo methods

of uncertainty propagation.[11] The resulting probability distribution of *r* is lognormal with a GM of 0.015 and GSD of 3.6 [90% CI of (0.002, 0.12)]. We believe that the upper bound of this probability distribution is reasonable because unshaved skin of the face could have an interception and retention fraction similar to the value for crew-cut hair.

4.1.4 Interception and Retention Fraction for Other Regions of Body

Interception and retention fractions, *r*, for other regions of the body can be assigned by analyzing similarities and differences between skin of the face and forearms and skin of other regions of interest. Accumulation of soil particles on special regions of the body, such as the back of the neck under a collar, is addressed in the next section.

Deposition and retention on other regions of body that contain little or no hair and are in a vertical position when an individual is standing presumably is similar to deposition and retention on skin of the face. Such regions of the body include the back and sides of the naked torso, shoulders, and forehead. Thus, for those regions, we use the interception and retention fraction for skin of the face, which is represented by a lognormal probability distribution with a GM of 0.015 and GSD of 3.6 [90% CI of (0.002, 0.12)].

Similarly, the interception and retention fraction for the forearms could be used for other regions of the body covered by hair, such as the upper legs or lower legs above the edge of boots.[12] Thus, for those regions, we use the interception and retention fraction for the forearms, which is represented by a lognormal probability distribution with a GM of 0.06 and GSD of 3.0 [90% CI of (0.01, 0.36)].

Interception and retention on the front of the torso may be complicated by the presence of abundant hair on some persons but little or no hair on others. For individuals with chest hair, the interception and retention fraction for the forearms probably is appropriate, while data for skin of the face should be appropriate for individuals with little or no chest hair. Since information regarding the presence of hair on the front of the torso is not normally available, a distribution

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[11] By taking 1,000 samples from the assumed probability distributions of a_h and s using Latin hypercube sampling implemented in Crystal Ball® software (www.crystalball.com), a probability distribution of *r* generated from 1,000 values of the ratio a_h/s was obtained.

[12] Similar to forearms, upper legs can be exposed in a horizontal position (e.g., while sitting).

that covers all situations could be used. If the probability distributions of *r* for the face and forearms/hands are combined with equal weights,[13] the best fit to the resulting probability distribution is a lognormal distribution with a GM of 0.03 and GSD of 3.9 [90% CI of (0.003, 0.28)]. This distribution is wider than either of the probability distributions of *r* for the face or forearms, because it accounts for uncertainty in interception and retention in both regions.

The probability distributions described in this section are relevant in cases of exposure of bare skin or while wearing loose clothing. The term "loose clothing" refers to clothing that does not significantly affect the ability of depositing material to contact skin. Interception and retention is reduced if tightly fit clothing is worn (see Section 5 for additional discussions on the effect of clothing). As discussed in previous sections, when interception and retention fractions (r) are estimated as a_h/s using probability distributions of the two parameters, values for many parts of the body should be constrained to not exceed 1.0.

4.1.5 Interception and Retention Fraction for Special Regions of Body

Retention of particles on skin can be enhanced in special regions, such as the back of the neck beneath a collar, the waistline under a belt, the shin at the edge of a boot, or behind the ears. In those regions, accumulation of particles per unit area of skin can be larger than the mass per unit area impacting the body surface, due to migration of particles that are intercepted on other parts of the body; i.e., the interception and retention fraction, *r*, can be greater than 1.0. For example, particles that impact hair on the back of the head and are not retained there can roll or bounce and be trapped in the space between a collar and the back of the neck. Similar processes are responsible for enhanced accumulation in the other special regions mentioned above.

The magnitude of the interception and retention fraction for the back of the neck under a collar can be estimated on the basis of simple geometrical considerations and available data. In the absence of a collar, or if a collar is very loose, the interception and retention fraction should be similar to that for skin of the face, given that the back of the neck at collar level is a nearly vertical surface with little or no hair.

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[13] The two distributions were sampled using Monte Carlo techniques and combined by assigning 50% weight to the interception and retention fraction for the face and 50% weight to the interception and retention fraction for the forearms.

If a collar is not loose, a fraction of the particles that impact hair in the occipital region and are not retained there may accumulate on skin under the collar, in addition to particles that impact the back of the neck. The lower limit of this fraction is zero, meaning that the amount of additional particles that accumulate under a collar is negligible (identical to the situation when a collar is loose). An upper limit of this fraction could be estimated at 20%, meaning that skin under a collar retains at most 20% of the particles that impact hair on the head and are not retained there. The estimate of 20% is obtained by observing that the surface area covered by hair in the occipital region can be as much as about 20% of the total surface area covered by hair. This value was chosen with respect to the total area covered by hair as opposed to the area of the entire head, because data from the volcanic ash studies are more abundant for hair. A uniform probability distribution between 0 and 0.2 was chosen to represent the uncertainty in the fraction (k_{hair}) of particles not retained on the scalp that are retained on skin under a collar.

The interception and retention fraction (r) for the neck under a collar, including particles that are initially intercepted by hair on the back of the head, is calculated as the skin contamination factor for the back of the neck ($a_{h\ neck}$) divided by the area of the neck beneath a collar (s_{neck}):

$$\begin{aligned} r_{neck} &= \frac{a_{h\ neck}}{s_{neck}} = \frac{\frac{a_{h\ face}}{s_{face}} s_{neck} + k_{hair} \cdot \left(1 - \frac{a_{h\ hair}}{s_{hair}}\right) \cdot s_{hair}}{s_{neck}} \\ &= r_{face} + k_{hair} \cdot (1 - r_{hair}) \cdot \frac{s_{hair}}{s_{neck}} \end{aligned} \tag{4-1}$$

The skin contamination factor for the back of the neck ($a_{h\ neck}$) is the sum of the mass of particles that are intercepted and retained on the back of the neck and the mass of particles that do not stick to hair but are retained on the back of the neck divided by the concentration of particles that are deposited on the ground. The area of the neck beneath a collar (s_{neck}) is about 1 × 5 inches to 1 × 6 inches, or 32 to 38 cm^2. Allowing for uncertainty, the area of this region is represented by a uniform probability distribution between 30 and 40 cm^2.

The interception and retention fraction (r_{neck}) for the back of the neck was estimated as described above by using Monte Carlo methods of propagating uncertainty in the various parameters. The resulting probability distribution has a median value (50th percentile) of 1.5, a

5th percentile of about 0.04, a 95th percentile of about 5, and a maximum value of about 8. This probability distribution is not well described by distribution functions, such as lognormal or triangular, that are used in this report to represent other uncertain parameters. A distribution function that reasonably fits the derived probability distribution is a gamma distribution (Decisioneering 2001) with 5th, 50th, and 95th percentiles at the values given above. This probability distribution is recommended to describe the uncertainty in the interception and retention fraction, *r*, for skin on the back of the neck under a collar. A majority of values in this probability distribution are greater than 1.0, which indicates a higher concentration on that part of the skin than the concentration of material deposited on the ground surface.

The probability distribution of the interception and retention fraction for the back of the neck under a collar is assumed to be a reasonable choice for other special regions of the body, including the waistline under a belt, shin at the edge of a boot, or behind the ears.

4.1.6 Interception and Retention Fraction for Material Resuspended by Winds

Another important consideration is the applicability of interception and retention fractions obtained from the volcanic ash study to deposition onto skin of fallout particles that are resuspended from the ground surface by winds. Interception and retention of wind-driven particles that impact the body of a standing person almost horizontally is conceptually similar to interception and retention of particles that settle by vertical motion on the body of a standing person, as in the case of depositing fallout. Fortunately, skin contamination factors (a_h) have been measured under conditions in which individuals performed normal activities (mostly walking or standing). Those conditions included no wind or the presence of mild winds or air currents, as well as exposure times of 1 to 7 hours indicated in Table 2-2 that are similar to exposure times experienced by some military personnel. Estimated interception and retention fractions thus are average values for a combination of environmental conditions, including situations where particles were carried (or at least influenced) by winds, and they can be used to estimate doses to skin from wind-driven resuspension. As noted in Section 3.3.3, the dose to skin increases with increasing wind speed, not because of an increase in the interception and retention fraction but because of an enhanced flux of particles that impact the body surface.

Wind-tunnel experiments performed by Asset and Pury (1954) and discussed in Section 2.2.2 included measurements using particles with a mass median diameter (MMD) of 6.5 μm and a wind speed of 5 mph (2.2 m s^{-1}). Results include an estimated efficiency of particle retention on the hairy part of the forearms of volunteers (a quantity similar to the interception and retention fraction, *r*). As indicated in Table 2-3, the efficiency of retention was found to vary from 0.0054 to 0.009. Similar experiments using particles with an MMD of 4.5 μm and a wind speed of 5.5 mph (2.5 m s^{-1}) were performed by Landahl (1944), who measured an efficiency of retention of about 0.02. In both experiments, skin and particles were dry. However, moist conditions similar those in the volcanic ash studies in Costa Rica can increase retention by a factor of 2.5 (Sheppard and Evenden 1994; see Section 2.1). Thus, if skin contamination occurs under moist conditions, the efficiency of retention estimated by Asset and Pury (1954) should increase to a range of 0.014 to 0.023, while the value reported by Landahl (1944) should increase to about 0.05. These estimates are consistent with the interception and retention fraction, *r*, for the forearms that we developed using data obtained in the volcanic ash studies, which has a geometric mean of 0.06 and 90% CI of (0.01, 0.34) (Table 4-1).

On the basis of arguments presented above, we believe that interception and retention fractions for descending fallout can be applied to radioactive material resuspended by winds.

4.2 Adjustments to Interception and Retention Fractions

As indicated in eq. (3-4) (Section 3.2), several adjustments factors are applied to interception and retention fractions, *r*, that are estimated on a mass basis from data obtained in the volcanic ash studies to develop effective interception and retention fractions, AR_f, on an activity basis that apply to conditions of exposure of military participants at atmospheric nuclear tests at NTS or in the Pacific. This section discusses recommended probability distributions of these adjustment factors, which are intended to apply to mixtures of radionuclides in fallout. These recommendations are summarized in Table 4-2.

4.2.1 Particle-Size Adjustment

The particle-size adjustment (PS_a) is a unitless factor that is developed using data which indicate that retention on skin depends on particle size. This adjustment factor accounts for differences between the particle-size distribution of airborne material impacting the body at a location of exposure of military personnel of interest and the particle-size distribution for which skin contamination factors (a_h) were measured in the volcanic ash studies.

Skin contamination factors (a_h) were estimated by measuring the mass of ash deposited on personnel during a few hours of fallout from eruption of the Irazu Volcano (Section 2.2.1). Measured particle-size distributions of volcanic ash on several days are summarized in Fig. 4-1. On the first day, those distributions had a median diameter of about 180 μm, and some particle diameters were as large as 350 μm. Three measurements of a_h for hair were reported for that day. Particle-size distributions on all other days included particles of diameter up to 300 μm, with a median diameter that varied between 60 and 80 μm. Only the skin contamination factors (a_h) that were measured after the first day, when the median particle size was about 70 μm on average, were used to estimate interception and retention fractions (r).

Kochendorfer and Ulberg (1967) indicated that the probability of retention on skin is inversely proportional to the median particle diameter (i.e., retention increases with decreasing median particle diameter as $1/d$) at least at diameters greater than 100 μm. At diameters less than 100 μm, those investigators suggested that the probability of retention remains constant. Similarly, in experiments performed by Sheppard and Evenden (1994) and Driver et al. (1989), retention was found to decrease with increasing particle size for diameters greater than 50 μm but was independent of particle size for diameters less than 50 μm.

On the basis of data summarized above, the dependence on particle diameter (d) of the probability that particles are retained on skin can be represented by the function:

$$s(d) = \begin{cases} a & \text{for } d < 50\,\mu\text{m} \\ \dfrac{50 \cdot a}{d} & \text{for } d \ge 50\,\mu\text{m} \end{cases} \qquad (4\text{-}2)$$

where a is a constant. As indicated by eq. (4-3) below, the value of a is not needed in estimating a particle-size adjustment factor.

4.2.1.1 *Exposure to Small Particles*

Given that the stabilization height of the cloud from a nuclear weapon detonation typically was about 30,000 ft or more, the settling time of 100-μm fallout particles from a cloud is on the order of a few hours or more (Glasstone and Dolan 1977; Sehmel and Hodgson 1976). Thus, at locations where exposure to descending fallout occurred at times more than few hours after detonation, the size distribution of fallout particles probably was weighted more towards smaller particles. When fallout contained mostly smaller particles of diameter less than 100 μm, the particle-size distribution can be assumed to have a median diameter of 50 μm or less. Since smaller particles are more efficiently retained on skin than larger particles, interception and retention fractions obtained from the volcanic ash studies should be increased, since they apply to exposures to distributions of particle sizes in which the median diameter was about 70 μm and a substantial fraction of particles had a diameter greater than 100 μm.

A similar situation occurs in cases of exposure to previously deposited fallout particles that were resuspended by winds or mild mechanical stresses (e.g., walking). Under such conditions, resuspended particles have diameters less than 100 μm, and the median diameter usually is less than 50 μm, even when previously deposited fallout contained a substantial fraction of larger particles (Sehmel 1984).

In this report, the term "small particles" refers to size distributions by mass in which most particles have diameters less than 100 μm and median diameter is less than 50 μm. In cases of exposure to small particles, it is expected that retention was enhanced, compared with retention in the volcanic ash studies, by a particle-size adjustment factor PS_a of about (70 μm)/(50 μm) = 1.4, where 70 μm is a median particle diameter in the volcanic ash studies (Fig. 4-1) and 50 μm is a maximum median particle diameter in a distribution of small particles.

A more rigorous approach to estimating PS_a should take into account the particle-size distributions in the volcanic ash studies shown in Fig. 4-1 and the particle-size distribution at locations where military personnel were exposed. If $p(d)$ is the probability density function of

the particle-size distribution by mass, the mass of particles that accumulate on skin is proportional to the integral $\int_0^\infty p(x)\,s(x)\,\mathrm{d}x$, where $s(x)$ is the probability of retention as a function of particle diameter given in eq. (4-2).[14]

If the mass particle-size distribution in the volcanic ash studies (Fig. 4-1) and the distribution for an exposure situation of interest are denoted by $p_1(d)$ and $p_2(d)$, respectively, the particle-size adjustment factor (PS_a) is given by:

$$PS_a = \frac{\int_0^\infty p_2(x)\,s(x)\,\mathrm{d}x}{\int_0^\infty p_1(x)\,s(x)\,\mathrm{d}x} \qquad (4\text{-}3)$$

Using the particle-size distributions in the volcanic ash studies and assuming that all particles at a location of exposure to descending or resuspended fallout have a diameter less than 50 μm, the particle-size adjustment factor (PS_a) estimated using eq. (4-3) varies from 1.3 to 1.5, where the range represents the minimum and maximum values of PS_a obtained using the different distributions $p_1(d)$ shown in Fig. 4-1. The central value of PS_a for exposure to small particles is about 1.4. Similarly, if 75% of radioactive particles to which military personnel were exposed have a diameter less than 50 μm and 25% have a diameter of 50 to 100 μm, the value of PS_a estimated using eq. (4-3) is 1.3, with a range of 1.2 to 1.4. If 50% of the particles have a diameter less than 50 μm and 50% have a diameter of 50 to 100 μm, PS_a becomes 1.2, with a range of 1.1 to 1.3.

To account for uncertainty in the size distribution of small particles at a location of exposure of interest and uncertainty in particle-size distributions in the volcanic ash studies, a lognormal probability distribution with a GM of 1.3 and GSD of 1.1 [90% CI of (1.1, 1.5)] can be assumed to represent the particle-size adjustment factor (PS_a) when exposure to particles of diameter less than 100 μm occurred (Table 4-2).

[14] In this and the following equation, the diameter of particles is denoted by *x* instead of *d*, so that the differential element d*x* is easily identified.

4.2.1.2 *Exposure to Large Particles*

Distributions of particle sizes in descending fallout at locations close to ground zero are weighted toward larger diameters (Miller 1969) compared with particle-size distributions in the volcanic ash studies. In this report, the term “large particles” denotes particle-size distributions by mass in which a large fraction of particles have diameters greater than 50 μm and the median is 100 μm or greater.

In cases of exposure to large particles, an interception and retention fraction, *r*, estimated from the volcanic ash studies should be corrected using a particle-size adjustment factor, PS_a, with an average value less than 1.0. If the particle-size distribution of large particles has a median diameter of 150 μm, for example, retention on skin should be reduced by a factor of about (70 μm)/(150 μm) = 0.47. By using eq. (4-3) and the distribution of particle sizes in fallout at 1.7 km from ground zero (GZ) of Shot DIABLO at NTS shown in Fig. 4-2, the estimated PS_a is 0.6. A range of 0.56 to 0.63 is obtained when different particle-size distributions of volcanic ash [$p_1(d)$; Fig. 4-1] are used to estimate PS_a. Similarly, the estimated PS_a for fallout particles at 4 km from ground zero of Shot SHASTA (Fig. 4-2) is 0.5, with a range of 0.48 to 0.55.

On the basis of these estimates and taking into account that the particle-size adjustment factor for large particles should be less than 1.0, a triangular probability distribution with a minimum at 0.4, mode at 0.8, and maximum at 1.0 can be used to represent the uncertainty in the particle-size adjustment factor (PS_a) when exposure to large particles of diameter mostly greater than 100 μm occurred (Table 4-2).

4.2.1.3 *Exposure to Unknown Particle Sizes*

If exposure to descending or resuspended fallout involved unknown particle sizes, a particle-size adjustment factor (PS_a) intermediate between values that apply to exposure to mostly large or mostly small particles should be appropriate. Furthermore, the uncertainty in this adjustment factor in such cases should be greater than in cases of known exposure to mostly large or small particles.

On the basis of the 95th percentile of the assumed lognormal probability distribution of PS_a for small particles of 1.5 (Section 4.2.1.1) and the minimum of the triangular probability distribution of PS_a for large particles of 0.4 (Section 4.2.1.2) and taking into account that a reasonable maximum PS_a for small particles would be somewhat greater than 1.5, we assume that the particle-size adjustment factor for unknown particle-size distributions can be represented by a uniform probability distribution with a minimum at 0.4 and maximum at 1.6; the median of this distribution is 1.0 (Table 4-2). We note that this probability distribution implies that, on average, that assumed size distribution of particles of unknown size is about the same as size distributions in the volcanic ash study.

4.2.2 Enhancement of Retention Due to Moisture on Skin

Retention of soil particles on skin is enhanced if skin is moist. Such an enhancement also should apply if soil is moist. There is limited information on the magnitude of such an effect. Data obtained by Sheppard and Evenden (1994) and described in Section 2.1 suggest that an enhancement in retention on skin due to moisture on skin or soil particles can be as high as a factor of 2.5. That study indicates that interception and retention fractions obtained from the volcanic ash studies should be adjusted downwards or upwards when applied to military personnel who were exposed under less or more humid conditions than in the volcanic ash studies, respectively. In addition, since the highest enhancement factor observed by Sheppard and Evenden (1994) is based on experiments in which a subject crushed and handled soil by hand under dry or moist conditions, an enhancement factor of 2.5 probably is an upper bound when applied to deposition of airborne soil particles on skin under the most humid conditions.

Separate probability distributions of the enhancement factor due to moisture (*EM*) are developed for dry and humid conditions. These distributions should apply to most exposures at NTS and in the Pacific, respectively.

Given the warm temperatures and high humidity in Costa Rica where the volcanic ash studies were carried out and given that study subjects were engaged in mild physical activity, estimates of interception and retention of particles obtained from those studies should be

applicable in the Pacific, with little adjustment.[15] The enhancement factor due to moisture (*EM*) for military personnel in the Pacific could be represented by a uniform probability distribution between 0.8 and 1.5. This distribution has a mean value slightly greater than 1.0 and, thus, incorporates an assumption that, on average, the effect of humidity in the Pacific is somewhat greater that in Costa Rica. The uncertainty in this enhancement factor accounts for an assumption that exposure conditions on any day in the Pacific can differ from the average exposure conditions in the volcanic ash studies in Costa Rica.

Conditions at NTS generally were much dryer than in Costa Rica.[16] Given that sweat evaporates rapidly in dry air, little buildup of moisture on skin of military personnel at NTS is expected. We assume that an enhancement factor due to moisture (*EM*) at NTS can be represented by a uniform probability distribution between 0.5 and 1.0, which gives a mean enhancement factor less than 1.0. This distribution reflects the belief that retention of particles on skin generally would be less at NTS than in Costa Rica, due to the dryer conditions.

4.2.3 Enrichment of Specific Activity

A set of experiments using soils labeled with uranium (Sheppard and Evenden 1994) discussed in Section 2.1 indicated that the activity per unit mass (specific activity) of soil on skin can be greater than the activity per unit mass of soil. This enrichment of specific activity occurred because skin retained smaller particles more efficiently and the activity on particle surfaces per unit mass of soil increased with decreasing particle size. The enrichment of specific activity should be largest for larger particles and minimal for the smallest particles. For sand particles, which tend to be relatively large, the enrichment of specific activity was as high as a factor of 8 to 10; such a high enrichment was obtained when many sand particles were too large to be retained efficiently on skin. For loamy soil, this enrichment factor varied from 2 to 7,

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[15] The temperature in the Marshall Islands varies between 75 and 85°F, and the average relative humidity is 80%. (Source: http:www.spc.int/prism/county/mh/stats/Geog/climate.htm; accessed September 2005.)

[16] For example, the monthly average relative humidity at 4 am in Las Vegas, which is close to the time of many detonations and subsequent exposures of military personnel, varies between 25% and 50% and the annual average is about 40%. The annual average relative humidity during the day is 20 to 30%, depending on the hour of the day. (Source: National Oceanic and Atmospheric Administration, http://www.wrh.noaa.gov/vef/climate/index.php; accessed September 2005.)

while the lowest enrichment factors (< 2) were observed for particles of soils rich in clay, which tend to have the smallest particle sizes and can readily adhere to skin.

The enrichment of specific activity described above occurs when radionuclides are preferentially found on the surface of particles, as in the experiments by Sheppard and Evenden (1994). If radionuclides are distributed in the volume of particles, no enrichment is expected for any particle-size distribution because the activity per unit mass would not depend on particle size. When fallout particles are formed after a nuclear detonation, fractionation of radionuclides occurs, and some radionuclides (mainly refractory elements) tend to be distributed in the volume of particles, while others (mainly volatile elements) tend to be distributed on the surface of particles (Hicks 1982; Section IV.C.2.1.2 of NRC 2003). Fallout at locations close to ground zero (e.g., within the boundary of NTS) is expected to be enriched in refractory elements that tend to be dispersed in the volume of larger particles, which fall to Earth relatively rapidly, and depleted in volatile elements that tend to be attached to the surface of smaller particles, which fall to Earth more slowly and, thus, are carried farther from ground zero by winds.

At locations far from ground zero, fallout particles tend to be small (diameters less than 100 μm, with a median diameter less than 50 μm), and they probably contain a higher proportion of volatile radionuclides (e.g., cesium, strontium and iodine) that are preferentially deposited on the surface of particles. Little or no enrichment of specific activity is expected when most radionuclides in fallout are volatile and, thus, are likely to be located on the surface of fallout particles and the particle-size distribution is heavily weighted towards small particles, which are efficiently retained by skin.

We assume that the uncertainty in the specific-activity enrichment factor (*EF*) for small particles can be represented by a left-triangular probability distribution with a minimum and mode at 1.0 and maximum at 2.0 (Table 4-2). The upper bound of this distribution was obtained by observing that the probability that 100 μm particles are retained on skin can be half the probability of retention of 50 μm particles, and that the probability of retention is expected to be constant for particle diameters less than 50 μm [Section 4.2.1, eq. (4-2)].

At locations close to ground zero, exposure to descending fallout mainly involves particle-size distributions that are heavily weighted towards large particles; exposure to mostly large particles also can occur in resuspension scenarios that involve vigorous stresses (e.g.,

resuspension by a nuclear detonation). Since fallout at such locations probably contains a higher proportion of refractory radionuclides that are distributed in the volume of particles, extreme enrichments of the specific activity of particles deposited on skin seem unlikely. However, since volatile radionuclides that are preferentially distributed on the surface of fallout particles are found even at locations close to ground zero, moderate levels of enrichment seem possible. For distributions of mostly large particles, available data indicate that a reasonable upper bound of the specific-activity enrichment factor (*EF*) is about 4. The lowest possible, but unlikely, value of *EF* is 1.0 (no enrichment of specific activity). Thus, in cases of exposure to mostly large particles, we assume that the uncertainty in the specific-activity enrichment factor (*EF*) can be represented by a triangular probability distribution with a minimum at 1.0, mode at 2.5, and maximum at 4.0 (Table 4-2).

In cases of exposure to unknown distributions of particle sizes, the specific-activity enrichment factor can vary from 1.0 (no enrichment) to 4.0 (maximum enrichment), but we expect that lower values are more likely. A log-uniform probability distribution between 1.0 and 4.0 is assumed to represent the uncertainty in the specific-activity enrichment factor (*EF*) in such cases; the median of this distribution is 2.0 (Table 4-2) and the mean is 2.2.

Discussions in this section about enrichment of the specific activity of particles deposited on skin apply to the entire inventory of radionuclides in fallout. Specific-activity enrichment factors (*EF*) could be developed for specific radionuclides; a distinction could be made, for example, between refractory and volatile radionuclides. However, it is impractical to develop such enrichment factors when fallout includes a large number of radionuclides, especially immediately after a detonation, and the extent of fractionation of different radionuclides in fallout from particular detonations is largely unknown.

4.2.4 Activity-Weight Adjustment Factor

Interception and retention fractions (*r*) derived from measurements of skin contamination factors (a_h) in the volcanic ash studies represent interception and retention on a weight (mass) basis; i.e., a_h is defined as the weight of volcanic ash particles retained on skin in a given region of the body divided by the weight of ash deposited per unit area on the ground surface. However, in fallout from nuclear weapon detonations, the activity particle-size distribution,

which is the quantity of interest in estimating dose, generally is not the same as the weight particle-size distribution. For example, in fallout at a distance of 4.2 miles from ground zero of Shot SHASTA at NTS, 24% of the weight consisted of particles of diameter less than 100 μm, but those particles carried only 0.75% of the total activity (Miller 1969; Figs. 13 and 15). Since most particles that could be retained on skin have a diameter less than 100 μm, the activity of particles retained on skin relative to the activity of fallout deposited on the ground would be smaller at locations close to ground zero at NTS than indicated by values of the interception and retention fraction, *r*, derived from the volcanic ash studies. In the example noted above, an activity-weight adjustment factor (*AW*) of 0.0075/0.24 = 0.03 could be used to reduce *r*. In a similar analysis of fallout at 2.5 miles from ground zero of Shot SHASTA, 32% of the weight consisted of particles of diameter less than 100 μm, but those particles carried only 0.30% of the total activity (Miller 1969; Figs. 11 and 12). Those data give an estimated activity-weight adjustment factor (*AW*) of 0.01. The same type of situation was observed in fallout at 1.1 miles from ground zero of Shot DIABLO at NTS. In that case, 30% of the weight of fallout particles consisted of particles of diameter less than 100 μm, but those particles carried only 0.60% of the total activity (Miller 1969; Figs. 8 and 9), and the resulting *AW* is 0.02. These estimates of *AW* are expected to represent lower bounds, because particles of diameter greater than 100 μm also can be retained on skin, albeit with a much lower probability than smaller particles.

On the basis of data on activity and weight particle-size distributions in fallout at NTS described above, the activity-weight adjustment factor (*AW*) that applies in cases of exposure to large fallout particles of diameter mostly greater than 100 μm could be represented by a lognormal probability distribution with a 90% CI of (0.01, 0.1) (Table 4-2). This distribution has a GM of 0.032 and GSD of 2.0. The GM is about the same as the estimated *AW* in fallout at 4.2 miles from ground zero of Shot SHASTA.

If exposure to small particles of diameter mostly less than 100 μm occurred, activity and weight particle-size distributions consisted mostly of particles than can be retained on skin. This situation probably occurred in most exposures far from ground zero in the Pacific, exposures to fallout that was resuspended by winds or light vehicular traffic, and exposures to the fraction of fallout resuspended by nuclear detonations at NTS that remained airborne after larger particles fell to Earth. In cases of exposure to mostly small particles, little adjustment to the interception

and retention fraction should be required to account for differences in activity and weight particle-size distributions. To account for uncertainty in the activity and weight particle-size distributions, the activity-weight adjustment factor (*AW*) for small particles could be represented by a right-triangular probability distribution with a minimum at 0.7 and a mode and maximum at 1.0 (Table 4-2). The median and mean of this distribution is 0.9.

When exposure to unknown distributions of particle sizes occurred, the activity-weight adjustment factor (*AW*) could range from a value that represents the low end of possible values for large particles to a value that represents the high end of possible values for small particles. However, extreme values should be unlikely. We represent an uncertain *AW* in such cases by a log-triangular probability distribution with a minimum at 0.01, mode (and median) at 0.1, and maximum at 1.0 (Table 4-2). The mean of this distribution is 0.15.

4.2.5 Exposure to Known Mixtures of Large and Small Particles

The development of adjustments to the interception and retention fraction (*r*) to account for particle size (Section 4.2.1), enrichment of specific activity (Section 4.2.3), and differences between activity and weight particle-size distributions (Section 4.2.4) involved assumptions that most of the activity of radionuclides was carried either by larger particles of diameter mostly greater than 100 μm or by smaller particles. Adjustment factors that would apply to unknown distributions of particle sizes also were considered.

There may be situations where military personnel at atmospheric nuclear tests were exposed to distributions of particle sizes in which substantial fractions of the activity of radionuclides were carried by small and large particles and those fractions can be estimated. In such situations, doses from dermal contamination can be estimated by estimating doses for the two size fractions separately using the appropriate adjustments to the interception and retention fraction for each size fraction and adding the two doses. Adjustment factors that apply to unknown distributions of particle sizes are not intended to be used in such cases.

4.3 Resuspension Factor

Measured resuspension factors associated with outdoor mechanical stresses range from 10^{-10} to 10^{-3} m^{-1}, and values ranging from 10^{-11} to 10^{-4} m^{-1} have been measured for resuspension by winds (Sehmel 1984). Resuspension factors relevant to processes modeled in this report were measured at sites where nuclear weapons were tested. Data on resuspension factors associated with vehicular traffic are given in Table 12.9 of Sehmel (1984) and summarized in Appendix A, Table A-9. Resuspension factors associated with winds are given in Table 12.7 of Sehmel (1984) and summarized in Appendix A, Table A-10. Except as noted, the reported resuspension factors presumably apply at a height above ground of about 1 m.

This section discusses available data and develops recommendations on probability distributions of resuspension factors for use in different exposure scenarios involving human activities or resuspension by winds. The recommended probability distributions are summarized in Table 4-3. In using resuspension factors to estimate dermal contamination, it is important to identify particle sizes to which a particular resuspension factor applies to ensure that appropriate values of the particle-size adjustment factor (PS_a), specific-activity enrichment factor (EF), and activity-weight adjustment factor (AW) are used to estimate effective interception and retention fractions (AR_f) [eq. (3-4) and Section 4.2]. Relevant particle sizes are noted in discussing particular resuspension factors.

4.3.1 Resuspension Associated with Human Activities

This section considers resuspension factors associated with vehicular traffic, walking, and helicopter take-off or landing. These stresses are potentially relevant in exposures of military personnel at atmospheric nuclear tests.

4.3.1.1 *Resuspension Due to Vehicular Traffic*

As indicated in Table IV.C.2 of the NRC (2003) report, a resuspension factor of 10^{-5} m^{-1} is often assumed in dose reconstructions for military personnel. That resuspension factor is intended to be an upper bound that applies to resuspension due to walking, most vehicular traffic,

and other light activities. In unusual scenarios involving assaults or marches behind armored vehicles at NTS, an upper-bound resuspension factor of 10^{-3} m^{-1} is assumed.

Resuspension factors associated with mechanical stresses, mainly moving vehicles, at desert sites where nuclear weapons were tested summarized in Table A-9 range from about 10^{-8} to nearly 10^{-3} m^{-1}. The highest values were measured at a height above ground of 0.3 m. On the basis of data on wind-driven resuspension summarized in Table A-10 that show a decrease in the resuspension factor with increasing height, the highest resuspension factors in Table A-9 could substantially overestimate values at a height of 1 m. A significant difference in resuspension at different heights above ground could be important at NTS, given that speed limits were imposed on vehicles in contaminated areas. However, reductions in wind-driven resuspension at a height of 1 m compared with 0.3 m may not apply to resuspension due to vehicular traffic, because the latter may provide more vigorous disturbances of surface soil than normal winds, even at low vehicle speeds. No other resuspension factors at 1 m associated with vehicular traffic at desert sites exceed 10^{-4} m^{-1}. At the other extreme, a resuspension factor as low as about 10^{-8} m^{-1} was reported at a desert site in Australia during a road survey at 1 to 2 days after a detonation. More common lower values of the resuspension factor are around 10^{-7} m^{-1}.

Given the quality of available data, we define a single probability distribution of the resuspension factor associated with vehicular traffic that applies at NTS and in the Pacific and at heights of 0 to 2 m above the ground surface; 2 m represents the maximum height of most individuals while standing on the ground. On the basis of data in Table A-9, we assume that the resuspension factor associated with vehicular traffic can be represented by a lognormal probability distribution with a 90% CI of (4×10^{-7}, 10^{-3}) m^{-1}; this distribution has a GM of 2×10^{-5} m^{-1} and GSD of 11 (Table 4-3). Since dust clouds generated by vehicular traffic presumably can reach 2 m in height, we assume that this resuspension factor can be applied in estimating dermal contamination in any region of the body.

Most exposures of military personnel to radionuclides that were resuspended by vehicular traffic probably involved smaller particles of diameter less than about 100 μm, regardless of the particle-size distribution on the ground surface. This would be the case if fallout consisted mainly of smaller particles (e.g., in most fallout on residence islands in the Pacific). At NTS, where most fallout consisted mainly of larger particles, resuspension by vehicular traffic

nonetheless could have resulted in exposure mainly to smaller particles in most cases. The extent of resuspension of larger particles by vehicles often was affected by speed limits at the site. In addition, when an individual was located at an appreciable distance from a moving vehicle, larger resuspended particles with very short settling times could have redeposited on the ground before exposure occurred.

There could be exceptions to the expectations described above. For example, if an individual was located close to moving vehicles, deposition of larger resuspended particles onto skin in lower regions of the body could have occurred. Marching behind groups of armored vehicles also could result in unusually high resuspension of larger particles and deposition onto skin when the greater height of a cloud of resuspended particles is taken into account. In such cases, it might be appropriate to assume that resuspended material contained a mixture of small and large particles, which could be considered separately in estimating dermal contamination.

4.3.1.2 *Resuspension Due to Walking*

Resuspension due to walking results in airborne concentrations of resuspended material that apparently decrease with height within 2 m of the ground surface. In contrast to resuspension due to vehicular traffic, it may be reasonable to develop separate resuspension factors associated with walking at heights close to the ground and at greater heights, because walking should be a considerably less vigorous disturbance than vehicular traffic.

Limited data summarized in Table A-9 indicate that resuspension factors associated with walking range from 1×10^{-6} to 3×10^{-4} m^{-1} at a height of 0.3 m. On the basis of those data, a reasonable probability distribution for use in estimating doses to skin from dermal contamination in lower regions of the body is a lognormal distribution with a 90% CI of $(10^{-6}, 3 \times 10^{-4})$ m^{-1}; this distribution has a GM of 2×10^{-5} m^{-1} and GSD of 5.7 (Table 4-3). The resuspension factor associated with walking to be used in estimating doses to skin in upper regions of the body presumably should be lower. On the basis of limited data summarized in Table A-9, a reasonable representation of the resuspension factor that applies in upper regions of the body is a lognormal probability distribution with a 90% CI of $(10^{-8}, 2 \times 10^{-6})$ m^{-1}; this distribution can be approximated by a distribution with a GM of 1×10^{-7} m^{-1} and GSD of 6.2 (Table 4-3).

Exposure to radionuclides that were resuspended by walking usually should involve small particles only. Although walking could result in contamination of feet and ankles by large particles as dust is kicked up by shoes, measured resuspension factors associated with walking do not account for this process.

4.3.1.3 *Resuspension Due to Helicopter Take-off or Landing*

A less common exposure scenario for military personnel involves resuspension of material due to helicopter take-off or landing and exposure at locations close to the site of resuspension. This type of scenario apparently occurred occasionally at NTS.

No measurements of resuspension factors associated with this type of stressor are available. However, helicopter take-off or landing results in strong local air currents that presumably generate substantially more vigorous lifting forces for particles on the ground and, thus, more resuspension than vehicular traffic. We assume that a reasonable representation of a resuspension factor in this case is a lognormal probability distribution with a 90% CI of (10^{-4}, 10^{-2}) m^{-1}; this distribution has a GM of 10^{-3} m^{-1} and GSD of 4.0 (Table 4-3).

It is reasonable to assume that particles of all sizes are resuspended during helicopter landing or takeoff. Therefore, a particle-size distribution of resuspended radioactive material consistent with the particle-size distribution on the ground should be assumed.

4.3.2 Wind-Driven Resuspension

Table A-10 summarizes measured resuspension factors associated with wind stresses at nuclear weapons testing sites. The lowest resuspension factors (3×10^{-10} and 2×10^{-9} m^{-1}) involved resuspension of plutonium at NTS. More typical low resuspension factors are about 10^{-8} to 10^{-7} m^{-1}. The largest measured resuspension factor was 3×10^{-4} m^{-1} at a height of 0.3 m above ground; a resuspension factor of 10^{-5} m^{-1} at a height of 0.6 m was reported in the same study. We assume that these data represent wind-driven resuspension at NTS and in the Pacific.

In addition to the decrease with increasing height above ground, resuspension factors associated with winds decrease over time after deposition (Anspaugh et al. 1975, 2002; Garger et

al. 1997b; Garland 1982, 1992; Nair et al. 1997). Data reported by Sehmel (1984) suggest that upper credibility limits of the resuspension factor associated with winds of 10^{-4} m^{-1} and 10^{-5} m^{-1} are reasonable at times after deposition within 6 months and at later times, respectively. On the basis of available data and an assumption that probability distributions of the resuspension factor would be applied at NTS and in the Pacific, reasonable lower credibility limits of a resuspension factor associated with winds are 10^{-8} m^{-1} at times after deposition within 6 months and 10^{-10} m^{-1} at later times.

Available data summarized above suggest that a lognormal probability distribution of the resuspension factor associated with winds with a 90% CI of (10^{-8}, 10^{-4}) m^{-1} (GM of 10^{-6} m^{-1}; GSD of 16) is reasonable at short times after detonation (Table 4-3). A lower resuspension factor should be used when exposure occurred at longer times after detonation. A reasonable assumption would be a lognormal probability distribution with a 90% CI of (10^{-10}, 10^{-5}) m^{-1} (GM of 3×10^{-8} m^{-1}; GSD of 33). These probability distributions are intended to apply to normal wind conditions; they may not apply in cases of intense winds of short duration.

If we define the uncertainty in a resuspension factor as the ratio of the 95th percentile of an assumed probability distribution to the median, uncertainties in the recommended resuspension factors associated with winds described above are a factor of 100 or more. These uncertainties are much larger than the uncertainty of a factor of 10 proposed by Anspaugh et al. (2002). That uncertainty factor is intended to apply to an annual-average resuspension factor. Given the variability in available data, and taking into account that the data usually represent resuspension over periods of much less than a year, we believe that an uncertainty factor of 10 could substantially underestimate the uncertainty in a resuspension factor associated with winds that applies over periods of a small fraction of a year. This is a potentially important consideration when exposures of military personnel often were of short duration, especially at NTS. Our recommended probability distributions are intended to account for this possibility. We also acknowledge, however, that an uncertainty factor on the order of 10 could be appropriate in cases of exposure over periods of several months or more, as often occurred on residence islands in the Pacific.

As in the case of resuspension due to walking, only smaller particles (diameters less than 100 μm) generally are resuspended by normal winds. This should be a reasonable assumption at any height above ground.

4.3.3 Resuspension by Nuclear Detonations at NTS

A scenario that occurred only at NTS involved resuspension of previously deposited fallout by a nuclear detonation and subsequent exposure of military personnel at locations near ground zero at times within a few hours after detonation. Inhalation doses in this type of scenario were assessed by Kocher et al. (2009). Results of that assessment of relevance to estimating dermal contamination are summarized below.

Resuspension of previously deposited fallout by a nuclear detonation at NTS occurred in two distinct regions: the region closest to ground zero, referred to as the thermal-pulse region, where the intense thermal pulse produced in a detonation was an important cause of resuspension, and the region beyond the thermal-pulse region, referred to as the blast-wave region, where significant resuspension was caused only by the blast wave and associated high winds. Resuspension was higher in the thermal-pulse region, due to the importance of the thermal pulse and associated precursor to the blast wave in that region and the higher wind speeds associated with the blast wave compared with wind speeds in the blast-wave region.

Exposure of military personnel may have occurred in both regions. Exposure in the thermal-pulse and blast-wave regions may have occurred when observers or maneuver troops entered those regions within a few hours after a detonation. In addition, forward observers were located in the blast-wave region at the time of some detonations, and those observers may have remained in the blast-wave region or entered the thermal-pulse region at times after a detonation. No forward observers were located in the thermal-pulse region at the time of a detonation.

In estimating dermal contamination by old fallout that was resuspended by a nuclear detonation, two parameters are used to describe resuspension. The first is the resuspension factor that applies to all previously deposited fallout, which incorporates an assumption that fallout particles of all sizes were resuspended to the same extent in the thermal-pulse and blast-wave regions. As described in Section 3.3.4, this resuspension factor would be used to estimate

dermal contamination of forward observers in the blast-wave region at the time of a detonation due to redeposition of large particles that carried nearly all the activity of resuspended old fallout and fell to Earth within a few minutes. During the short period of redeposition of large particles, dermal contamination of forward observers due to the slower redeposition of small particles that carried a very small fraction of the activity of resuspended old fallout would be negligible. The second parameter, which would be used to estimate dermal contamination of personnel who entered the thermal-pulse or blast-wave region at some time after a detonation and dermal contamination of forward observers during times spent in the blast-wave region after large particles were redeposited, is the fraction of the activity of resuspended fallout that was carried by small particles and remained airborne for times as long as a few hours.

Kocher et al. (2009) judged that the resuspension factor that applies to all previously deposited fallout in the thermal-pulse region can be represented by a lognormal probability distribution with a GM of 10^{-3} m^{-1} and 90% CI of (10^{-4}, 10^{-2}) m^{-1} (GSD of 4.0). If it is assumed that resuspended material in the thermal-pulse region would be distributed uniformly to a height of 100 m, a resuspension factor of 10^{-3} m^{-1} corresponds to an assumption that 10% of all old fallout in that region was resuspended. In the blast-wave region, the resuspension factor that applies to all previously deposited fallout was assumed to be much lower and more uncertain, due to the less intense stressors and the decrease in wind speed associated with a blast wave with increasing distance beyond the thermal-pulse region. A lognormal probability distribution with a GM of 10^{-5} m^{-1} and 90% CI of (10^{-7}, 10^{-3}) m^{-1} was assumed (GSD of 16; Table 4-3). Again, this resuspension factor would be used to estimate dermal contamination of forward observers in the blast-wave region at the time of a detonation due to redeposition of large particles that carried nearly all the activity in resuspended old fallout.

The fraction of the activity of resuspended fallout that was carried by small particles and remained airborne for an extended period after a detonation should be about the same as the inhalable fraction of resuspended fallout estimated by Kocher et al. (2009), which was assumed to consist of particles of diameter less than 100 μm. On the basis of data on activity particle-size distributions in fallout at NTS, inhalable particles carried a very small fraction of the activity of radionuclides in resuspended old fallout. Kocher et al. (2009) judged that the inhalable fraction of the activity of resuspended fallout that remained airborne for an extended period in the

thermal-pulse and blast-wave regions can be represented by a lognormal probability distribution with a GM of 0.01 and 90% CI of (0.001, 0.1); the GSD of this distribution is 4.0.

Combining the probability distributions of the two parameters described above gives a resuspension factor that applies to small particles in old fallout that was resuspended by a detonation and could be deposited on skin of military personnel who were exposed in the thermal-pulse or blast-wave region at times after large resuspended particles had redeposited and were no longer airborne. Limits of the 90% CI of the resulting probability distribution are rounded to the next lowest or highest power of 10 to better represent uncertainties in these estimates. In the thermal-pulse region, the desired resuspension factor is represented by a lognormal probability distribution with a GM of 10^{-5} m^{-1} and 90% CI of (10^{-7}, 10^{-3}) m^{-1} (GSD of 16; Table 4-3). The resuspension factor that applies to all previously deposited fallout and the inhalable fraction of resuspended fallout (i.e., the fraction of the resuspended activity carried by small particles) contribute about equally to this uncertainty. In the blast-wave region, the desired resuspension factor is represented by a lognormal probability distribution with a GM of 10^{-7} m^{-1} and 90% CI of (10^{-10}, 10^{-4}) m^{-1} (GSD of 67; Table 4-3). The resuspension factor that applies to all previously deposited fallout is the dominant source of uncertainty.

Equations (3-28) and (3-31) in Section 3.3.4 present a model to estimate dermal contamination of forward observers due to deposition of large fallout particles that were resuspended by the blast wave and were redeposited on the ground surface within a few minutes. In applying that model, the height above ground over which resuspended material was distributed [the parameter H in eq. (3-31)] should be about 10 to 30 m (Kocher et al. 2009). The resuspension factor, RF, in that model is a value that applies to all old fallout in the blast-wave region. At times after all large particles fell to Earth, dermal contamination due to deposition of smaller fallout particles that remained airborne is estimated using a deposition velocity, V_D (or wind speed, V_W).

4.4 Deposition Velocity

Deposition velocities onto the ground surface for particles of diameter between 0.001 and 100 μm are provided by Sehmel (1984) as function of particle density. Deposition velocities of

material resuspended by human activities (e.g., vehicular traffic, agricultural machines) were estimated by Garger et al. (1998) from measurements in areas that experienced fallout of ^{137}Cs from the Chernobyl accident; particle diameters in that study ranged from 0.1 to 100 μm. Deposition velocities onto skin, hair and clothing for particles of diameter less than 10 μm in the form of aerosols released in an indoor environment were measured by Fogh et al. (1999), as described in Section 2.2.3. These three sources indicate that deposition velocities are small over the range of particle sizes studied, i.e., between 0.0001 and 1 m s^{-1} in Sehmel (1984), 0.009 and 0.06 m s^{-1} in Garger et al. (1998), and 0.001 and 0.02 m s^{-1} in Fogh et al. (1999).

In the studies noted above, the surface onto which deposition occurred was stationary. However, individuals who are exposed to airborne particles in outdoor environments often are in motion, and deposition onto the human body depends on an individual's speed of motion relative to ambient air (Kochendorfer and Ulberg 1967). A walking speed normally is about 3 mph (1.3 m s^{-1}) and may range from 0.1 m s^{-1} (very slow walk at 0.25 mph) to 5 m s^{-1} (11 mph; running short distances). The lower bound of this range is equivalent to expected settling velocities for particles of diameter about 40 μm. Larger speeds relative to ambient air are possible in other situations, such as riding in the back of a truck. When a person walks for a longer period of time (e.g., an hour or more), the average speed varies within a narrower range, probably between 0.5 m s^{-1} (1.1 mph) and 3 m s^{-1} (6.7 mph).

Particles with a given settling velocity in still air (e.g., 0.1 m s^{-1}) can impact only the non-vertical surfaces of a stationary individual (e.g., top of the head, shoulders). If an individual moves horizontally at 1 m s^{-1}, particles will impact the body almost horizontally, thus offering a much larger surface area for particle deposition. A higher particle velocity at the body surface usually increases the probability of impaction due to particle inertia, which is important for particles of diameter greater than 10 μm (Kochendorfer and Ulberg 1967; Sehmel 1984).

For purposes of estimating doses to skin from dermal contamination for individuals in motion in a dust cloud, we believe that "deposition" velocities of about 1 m s^{-1} can be assumed. In the absence of wind, a deposition velocity for use in modeling deposition of airborne particles onto skin while walking could be represented by a triangular probability distribution with a minimum at 0.5 m s^{-1}, mode at 1.0 m s^{-1} and maximum at 3 m s^{-1} on the basis of assumptions

described above (Table 4-2). Deposition velocities can be 7 to 14 m s^{-1} if exposure occurred while riding in the back of a truck at 15 to 30 mph.

If significant winds occurred at the time of exposure, a probability distribution of the wind speed described in the following section could be used as a surrogate for the deposition velocity, since modeling of wind-driven resuspension (Section 3.3.3) is the same as modeling of resuspension by human activities (Section 3.3.2) when the deposition velocity, V_D, is replaced by the wind speed, V_W.

4.5 Wind Speed

Ideally, measurements of wind speed would be available at locations and times of exposure. In the absence of measurements, a wind speed must be assumed in estimating doses from dermal contamination by material resuspended by winds. A long-term average wind speed at NTS[17] is 4 m s^{-1}, with monthly averages ranging from 3.6 to 5 m s^{-1}. Average winds in the Pacific are stronger. At Kwajalein,[18] the annual average wind speed is 6 m s^{-1}, with monthly averages ranging from 4 to 7.5 m s^{-1}. On Majuro Atoll,[19] monthly average wind speeds range from 3 to 6 m s^{-1}.

Data described above indicate that the long-term average wind speed at NTS can be represented by a uniform probability distribution between 3 and 5 m s^{-1} (mean of 4 m s^{-1}). In cases of short-term exposures at NTS over periods of a several hours or less, which were common, the average wind speed should be more uncertain and could be represented by a uniform probability distribution between 2 and 6 m s^{-1}. For exposures on residence islands in the Pacific over periods of weeks or months, the long-term average wind speed can be represented by a uniform probability distribution between 3 and 7 m s^{-1} (mean of 5 m s^{-1}).

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[17] Source: data for Desert Rock-Mercury obtained from Western Regional Climate Center; www.wrcc.dri.edu/ htmlfiles/westwind.final.html; accessed September 2005.

[18] Source: Western Regional Climate Center; http://www.wrcc.dri.edu/cgi-bin/clilcd.pl?pi40604; accessed September 2005.

[19] Source: http://www.spc.int/prism/country/mh/stats/Geog/climate.htm; accessed September 2005.

4.6 Dose-Rate Factors

The main concern in cases of dermal contamination by radionuclides is exposure of radiosensitive tissues in the basal layer of skin to electrons (primarily beta particles). Exposure to radionuclides that emit alpha particles also is a potential concern. Dose-rate factors and their uncertainties for these two radiation types are discussed separately in the following sections. A dose-rate factor is defined as the dose rate per unit concentration of a radionuclide or radionuclides on the body surface.

4.6.1 Dose-Rate Factors for Beta-Emitting Radionuclides

Doses to skin from dermal contamination by beta-emitting radionuclides are estimated using published dose-rate factors that apply to radiosensitive tissues in the basal layer of skin at depths of about 4 to 10 mg cm^{-2}; the average depth is about 7 mg cm^{-2} (ICRP 1975; Charles 1986). A depth of 7 mg cm^{-2} is about 70 μm at a density of tissue of about 1 g cm^{-3}. The appropriate depth depends on the location of interest on the body surface.

An important challenge in estimating doses from beta-emitting radionuclides in fallout from detonation of a nuclear weapon is that fallout contains many radionuclides of widely varying half-lives. Since exposure can occur at any time after a detonation, it is impractical to estimate doses using radionuclide-specific dose-rate factors that are applied to the concentration of each radionuclide. However, as indicated in the following discussions, electron doses to skin can be estimated using a nominal dose-rate factor that applies to the activity concentration of all beta-emitting radionuclides combined and is largely independent of time after a detonation.

In this report, doses to skin from beta-emitting radionuclides on the body surface are estimated on the basis of a dose-rate factor that applies at a depth of 7 mg cm^{-2}. In estimating doses at other depths, the dose-rate factor at 7 mg cm^{-2} is adjusted upward or downward by a factor that accounts for the depth of radiosensitive tissues of skin in the region of interest as:

$$DRF_{skin} = DRF_{7\,mg\,cm^{-2}} \cdot SDMF \qquad (4\text{-}4)$$

where

DRF_{skin} = dose-rate factor at assumed depth of radiosensitive tissues for radionuclides deposited on skin (rem h^{-1} per μCi cm^{-2});

$DRF_{7\ mg\ cm^{-2}}$ = dose-rate factor at depth of 7 mg cm^{-2} (rem h^{-1} per μCi cm^{-2});

$SDMF$ = skin-depth modification factor (unitless) to account for assumption of a nominal depth of radiosensitive tissues of skin in region of interest different from 7 mg cm^{-2} and to account for variability in depth of radiosensitive tissues in that region.

Appropriate values of the dose-rate factor (*DRF*) at a depth of 7 mg cm^{-2} and the skin-depth modification factor (*SDMF*) at other depths are discussed in the following two sections.

4.6.1.1 *Nominal Dose-Rate Factor at Depth of 7 mg cm^{-2}*

Dose rates to skin from electrons per unit activity concentration of radionuclides on the body surface (dose-rate factors, *DRF*) were calculated by Kocher and Eckerman (1987) for many radionuclides of interest on the basis of an assumption that concentrations are uniform. Given that the electron range in tissue is less than 2 cm at most energies that occur in radioactive decay, it can be assumed that a surface area as small as 15 cm^2 is effectively infinite in extent for the purpose of estimating electron dose to skin at depths below the center of a contaminated area. Therefore, since dermal contamination by particles from nuclear weapons fallout[20] is expected to cover areas of skin larger than 15 cm^2 and to be relatively uniform in a given region of the body (e.g., face, arms, legs, or back), dose-rate factors for uniform dermal contamination can be applied to estimate doses from contamination by fallout. Doses to skin due to single “hot” particles are not considered in this report.

As noted above, it is impractical to estimate electron doses to skin using dose-rate factors for specific radionuclides when the contribution of each radionuclide to the total activity concentration of all radionuclides combined depends on time after a detonation. A more practical approach is to develop a nominal dose-rate factor that represents the dose rate per unit activity concentration all radionuclides in fallout combined.

[20] This discussion refers to particles in descending fallout and fallout particles resuspended by winds or mechanical stresses.

Development of a nominal dose-rate factor for all radionuclides in fallout combined is facilitated by calculations of the dose-rate factor as a function of electron energy (Kocher and Eckerman 1987) shown in Fig. 4-3. Those calculations indicate that the dose-rate factor is largely independent of energy in a plateau region where energies are slightly above the minimum energy required for an electron to penetrate to the depth of radiosensitive tissues. For example, at a depth of 8 mg cm^{-2}, the dose-rate factor is nearly constant at energies above 0.1 MeV. Consequently, as indicated in Table 1 of Kocher and Eckerman (1987), dose-rate factors are nearly the same for specific radionuclides with an average energy of emitted electrons in the plateau region (e.g., above about 0.1 MeV at a depth of 8 mg cm^{-2}).

On the basis of calculations by Kocher and Eckerman (1987) described above, a nominal dose-rate factor can be estimated for all radionuclides in fallout combined that is largely independent of the contribution of each radionuclide to the total activity concentration on the body surface and, therefore, applies at any time after a detonation. Calculated dose-rate factors similar to those in the plateau region in Fig. 4-3, where the dose-rate factor is largely independent of energy, were used by Barss (2000) to develop a dose-rate factor at a depth of 7 mg cm^{-2} for mixtures of radionuclides in fallout of 9 rem h^{-1} per μCi $cm^{-2}{}_{skin}$.[21]

The nominal dose-rate factor for all radionuclides in fallout combined at a depth of 7 mg cm^{-2} given above is an upper bound. A more realistic estimate would take into account that some radionuclides in fallout emit electrons of average energy less than about 0.1 MeV and, thus, do not contribute significantly to the electron dose to skin. In addition, calculations by Kocher and Eckerman (1987) assume that electrons are emitted in an infinite tissue medium, rather than at an air-tissue interface, which results in an overestimate of the contribution to the dose from backscattering of electrons that are emitted in directions away from the body surface.

By considering all fission products (plus activation products ^{237}U and ^{239}Np) that would be present at 2 days and 4 years after a detonation (Trabalka and Kocher 2007), we estimated that the dose-rate factors for mixtures of radionuclides in fallout at those times are 5.1 and 6.4 rem h^{-1} per μCi cm^{-2}, respectively. Thus, accounting for low-energy beta emitters results in

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[21] This dose-rate factor applies, for example, to the high-energy beta emitters ^{90}Sr and ^{90}Y and is a good approximation for other radionuclides with average energies of emitted electrons greater than about 0.1 MeV. The dose-rate factor for mixtures of radionuclides in fallout estimated by Barss (2000) also includes a contribution of about 5% from photons. Such a small contribution can be neglected.

nominal dose-rate factors for all radionuclides in fallout combined at a depth of 7 mg cm^{-2} that are lower by about 40% at times shortly after a detonation and about 30% at much longer times than the dose-rate factor of 9 rem h^{-1} per μCi cm^{-2} discussed by Barss (2000).

When backscattering in tissue is assumed, as in the calculations by Kocher and Eckerman (1987), backscattered electrons impact the body surface only at locations close to the source, due to the short ranges of emitted electrons in tissue, and, therefore, contribute to the dose to radiosensitive tissues only at locations of contamination. However, the range of emitted electrons in air often is much greater than the dimensions of a source area on the body surface, even when the entire body is contaminated. Therefore, when backscattering occurs in air, some backscattered electrons either do not impact the body surface at locations close to the source or they miss the body entirely. In either case, the contribution to the dose to skin at locations of contamination from backscattered electrons is reduced compared with the dose obtained by assuming backscattering in tissue.

Calculations by Cross et al. (1992) indicate that neglect of backscattering in air results in overestimates of the dose to radiosensitive tissues of skin when the maximum (endpoint) energy of electrons emitted in beta decay of a radionuclide exceeds 0.15 MeV. The factor by which the dose is overestimated increases nearly linearly with increasing endpoint energy to about 1.4 at an energy of 2 to 3 MeV and then decreases at higher endpoint energies. The maximum backscatter factor of about 1.4 applies, for example, to electrons emitted in decay of ^{90}Y. A multiplicative correction to the nominal dose-rate factor to account for the effect of backscattering is the reciprocal of the backscatter factor calculated by Cross et al. (1992). Thus, we represent an uncertain backscatter correction to a nominal dose-rate factor for mixtures of radionuclides in fallout by a uniform probability distribution between 0.7 and 1.0. This correction factor is assumed to apply at any depth of radiosensitive tissues and in any part of a contaminated region of any size, even though Cross et al. (1992) calculated a backscatter correction only at a depth of 7 mg cm^{-2} on the axis of a source of area 100 cm^2.

Sources of uncertainty in calculated dose-rate factors that were considered by Kocher and Eckerman (1987) include use of the point-kernel method, use of approximate representations of continuous spectra of electrons from beta decay, and uncertainties in energies and intensities of electrons emitted by radionuclides. These uncertainties all should be small (about 10% or less).

We represent the combined effect of these uncertainties by a normal probability distribution with a 90% CI of (0.9, 1.1).

Another factor that can affect electron doses to skin from exposure to radioactive particles on the body surface is absorption of electrons by the particles. Most particles that are retained on skin for a significant period of time have diameters of 50 μm or less (Section 2.1). At a density of fallout particles at NTS of about 2.7 g cm^{-3} (the density of fallout particles in the Pacific may be lower), a 50-μm particle at NTS provides a maximum shielding equivalent to about 14 mg cm^{-2} of tissue. If ^{90}Y is selected as a representative high-energy beta emitter, an additional 14 mg cm^{-2} of shielding reduces the dose-rate factor by about 40%; this estimate is based on interpolation of dose-rate factors for ^{90}Y at different depths in tissue in Table 1 of Kocher and Eckerman (1987). A reduction of 40% is a maximum effect at this particle size, because some radionuclides would be shielded by only a fraction of the particle diameter and radionuclides on the underlying surface (if any) would not be shielded. This reduction could be increased to perhaps 50% to take into account that the dose-rate factor for mixtures of radionuclides would decrease as the thickness of shielding increases when fewer radionuclides would have dose-rate factors in the plateau region of curves in Fig. 4-3.

We also consider that some particles that are retained on skin should have a diameter greater than 50 μm, and that the shielding provided by such particles would be greater than the estimate given above. For example, for a 150-μm particle of density 2.7 g cm^{-3}, which is equivalent to 40 mg cm^{-2} of tissue, the reduction in the dose-rate factor at high electron energies would be slightly less than a factor of two, and the reduction to account for mixtures of radionuclides that emit various average energies of beta particles probably would be greater than a factor of two. However, most of the dose to skin is expected to be due to particles of diameter less than 50 μm, for which the probability of retention on skin is the highest (Section 4.2.1).

On the basis of the foregoing considerations, we assume that the effect of shielding by particles is a reduction of the dose-rate factor for mixtures of radionuclides in fallout by a factor that can be represented by a triangular probability distribution with a minimum at 0.5, mode at 0.8 (i.e., half the maximum reduction due only to shielding by a 50-μm fallout particle), and maximum at 1.0.

By applying the probability distributions developed above to represent uncertainties in a backscatter correction, dose-rate factors calculated by Kocher and Eckerman (1987), and a correction for shielding provided by particles to the estimated dose-rate factor for mixtures of radionuclides in fallout at 2 days of 5.1 rem h^{-1} per μCi cm^{-2}, a nominal dose-rate factor at a depth of 7 mg cm^{-2} for mixtures of radionuclides in 2-day old fallout in rem h^{-1} per μCi cm^{-2} can be represented by a triangular probability distribution with a minimum at 1.6, mode at 3.2, and maximum at 5.4. Similarly, a nominal dose-rate factor for mixtures of radionuclides in 4-year old fallout in the same units can be represented by a triangular probability distribution with a minimum at 2.0, mode at 4.1, and maximum at 6.8.

The number of radionuclides and their relative activities in fallout change with time. However, given that the dose-rate factors for all radionuclides combined in 2-day and 4-year old fallout are similar, it is reasonable to develop a single dose-rate factor that applies at any time after a detonation. On the basis of the probability distributions at the two times given above, a nominal dose-rate factor at a depth of 7 mg cm^{-2} for mixtures of radionuclides in fallout in units of rem h^{-1} per μCi cm^{-2} that applies at any time can be represented by a triangular probability distribution with a minimum at 1.6, mode at 3.7, and maximum at 6.8 (Table 4-2).

4.6.1.2 *Skin-Depth Modification Factor*

Dose-rate factors for beta-emitting radionuclides discussed in the previous section apply at a depth below the body surface of 7 mg cm^{-2} (70 μm), which is considered to be the average thickness of the epidermis. However, radiosensitive tissues in the basal layer of skin are located at other depths in certain regions of the body. For example, radiosensitive tissues in skin of the face are located at an average depth of about 4 mg cm^{-2} (40 μm), while radiosensitive tissues in skin of the forearms and lower legs are located at an average depth of about 8 mg cm^{-2} (80 μm) (ICRP 1975; Charles 1986; Whitton 1973). The thickness of the epidermis is greatest on the palms of the hands and soles of the feet. Those regions also exhibit the largest variation in thickness, which ranges from about 60 mg cm^{-2} (600 μm) on horny pads of the palms and soles to as low as about 20 mg cm^{-2} (200 μm) in other areas. A thickness of 40 mg cm^{-2} (400 μm) is generally accepted as an average in those regions.

The nominal dose-rate factor for all radionuclides in fallout combined at a depth of 7 mg cm^{-2} developed in the previous section needs to be adjusted using a skin-depth modification factor (*SDMF*) to estimate doses to skin from dermal contamination in regions of the body where radiosensitive tissues are located at a different depth. This adjustment factor is developed on the basis of two considerations. The first is the dependence of the dose-rate factor (*DRF*) in the plateau region in Fig. 4-3, where the dose-rate factor is largely independent of energy, on the depth of radiosensitive tissues. As the depth increases, the dose-rate factor in the plateau region decreases, and vice versa. Second, as the depth of radiosensitive tissues decreases (increases), the number of radionuclides with a dose-rate factor in the plateau region may increase (decrease), which results in an increase (decrease) in the dose-rate factor for mixtures of radionuclides in fallout relative to the nominal dose-rate factor at a depth of 7 mg cm^{-2}. The contribution of the second effect to a skin-depth modification factor does not represent a double accounting of a similar effect that is incorporated in the probability distribution of the dose-rate factor discussed in the previous section, because that adjustment applies at a depth of 7 mg cm^{-2} where a skin-depth modification factor is not used [eq. (4-4)].

The two adjustments that are incorporated in a skin-dose modification factor should be positively correlated, given the relationship between the depth of radiosensitive tissues and the number of radionuclides with a dose-rate factor in the plateau region in Fig. 4-3 noted above. A perfect positive correlation (correlation coefficient of +1.0) between the dose-rate factor in the plateau region and the number of radionuclides with a dose-rate factor in that region is assumed. If this correlation were not taken into account, the uncertainty in the skin-dose modification factor would be underestimated.

In the following sections, we develop probability distributions of the skin-depth modification factor (*SDMF*) by taking into account the two adjustments to a dose-rate factor (*DRF*) at 7 mg cm^{-2} and their positive correlation described above and the variability (range) in depths of radiosensitive tissues in different regions of the body where the nominal depth is assumed to be 4, 8, or 40 mg cm^{-2}. The variability in the depths of radiosensitive tissues (thickness of the epidermis) is described by ICRP (1975), Charles (1986), and Whitton (1973).

4.6.1.2.1 *Skin-depth modification factor at nominal depth of 4 mg cm^{-2}*

In some regions of the body, such as the face, forehead, neck, shoulders, torso, and upper legs, radiosensitive tissues in the basal layer of skin are located at an average depth of 4 mg cm^{-2}. The minimum depth in those regions is 2 mg cm^{-2} (ICRP 1975; Charles 1986; Whitton 1973). A maximum depth of 7 mg cm^{-2} is given by ICRP (1975) and Charles (1986), whereas Whitton (1973; Figs. 1 and 2) reports a maximum depth of about 10 mg cm^{-2}.

We first consider the contribution to the skin-depth modification factor (*SDMF*) that accounts for the dependence of the dose-rate factor in the plateau region of Fig. 4-3 on the depth of radiosensitive tissues. Dose-rate factors as a function of energy in Fig. 4-3 and dose-rate factors for specific radionuclides in Table 1 of Kocher and Eckerman (1987) indicate that a contribution to *SDMF* of 1.3 describes the increase in dose-rate factor in the plateau region when the depth in tissue decreases from 7 to 4 mg cm^{-2}. By assuming that the maximum depth in tissue is about 10 mg cm^{-2}, as reported by Whitton (1973), extrapolation of dose-rate factors for higher-energy beta emitters at depths of 4 and 8 mg cm^{-2} gives a minimum of the contribution to *SDMF* of 0.8. At an assumed minimum depth in tissue of 2 mg cm^{-2}, a maximum of the contribution to *SDMF* due to the increase in dose-rate factor in the plateau region of 1.4 is obtained by extrapolation of dose-rate factors for high-energy beta emitters at depths of 4 and 8 mg cm^{-2} in Table 1 of Kocher and Eckerman (1987).

On the basis of estimates given above, the contribution to the skin-depth modification factor (*SDMF*) that applies to a nominal dose-rate factor for higher-energy beta emitters—i.e., to the dose-rate factor in the plateau region of curves in Fig. 4-3—at a depth of 7 mg cm^{-2} to obtain a nominal dose-rate factor at a depth of 4 mg cm^{-2} can be represented by a triangular probability distribution with a minimum at 0.8, mode at 1.3, and maximum at 1.4.

Data in Table 1 of Kocher and Eckerman (1987) indicate that few radionuclides show a large increase in dose-rate factor as the depth of radiosensitive tissues decreases from 7 to 4 mg cm^{-2}; i.e., few radionuclides with a dose-rate factor below the plateau region in Fig. 4-3 at a depth of 7 mg cm^{-2} have a dose-rate factor in the plateau region at a depth of 4 mg cm^{-2}. Therefore, there should be little increase in the dose-rate factor for mixtures of radionuclides in fallout due to an increase in the number of radionuclides that contribute significantly to the dose

as the depth decreases from 7 to 4 mg cm^{-2} or even to 2 mg cm^{-2}. We assume that this increase can be represented by a uniform probability distribution between 1.0 and 1.2. The effect of increasing the depth to as much as 10 mg cm^{-2}, which could reduce the number of radionuclides that contribute significantly to the dose, perhaps would be somewhat less and is assumed to be represented by a uniform probability distribution between 0.9 and 1.0. Thus, in this case, we assume that the contribution to the skin-dose modification factor (*SDMF*) to account for a difference in the number of radionuclides in fallout with a dose-rate factor in the plateau region can be represented by a uniform probability distribution between 0.9 and 1.2.

By combining the probability distributions of the two contributions described above and assuming that they are perfectly positively correlated, the skin-depth modification factor (*SDMF*) at a nominal depth of 4 mg cm^{-2} can be represented by a triangular probability distribution with a minimum at 0.7, mode at 1.3, and maximum at 1.7 (Table 4-2). The assumed correlation between the two contributions has only a small effect on the resulting probability distribution of the skin-depth modification factor compared with an assumption of no correlation.

4.6.1.2.2 *Skin-depth modification factor at nominal depth of 8 mg cm^{-2}*

In some regions of the body, such as the forearms and lower legs, radiosensitive tissues in the basal layer of skin are located at an average depth of 8 mg cm^{-2} (80 μm). Data summarized by ICRP (1975) indicate that the thickness of the epidermis is 50–65 μm on the back of the forearms, 34–65 μm on the front of the forearms, and 40–80 μm on the lower legs. Data in Figs. 4 and 5 of Whitton (1973) indicate that the maximum depth of the basal layer in these regions is 16 mg cm^{-2} (160 μm). The minimum depth indicated in Figs. 4 and 5 of Whitton (1973) is 4 mg cm^{-2}, which is in reasonable agreement with the lowest value of 3.4 mg cm^{-2} (34 μm) reported by ICRP (1975).

We assume that 8 mg cm^{-2} is a reasonable central estimate of the depth of radiosensitive tissues in regions of the body where the nominal value is assumed to apply, and that the depth in those regions ranges from 4 to 16 mg cm^{-2}. Using data in Table 1 of Kocher and Eckerman (1987) and Fig. 4-3, the approach to estimating a skin-depth modification factor (*SDMF*) described in the previous section leads to the following results at a nominal depth of 8 mg cm^{-2}:

- The contribution to the skin-depth modification factor that accounts for the variation in the dose-rate factor for higher-energy beta emitters in the plateau region of Fig. 4-3 as the depth of radiosensitive tissues ranges from 4 to 16 mg cm^{-2}, relative to the dose-rate factor in the plateau region at a depth of 7 mg cm^{-2}, can be represented by a triangular probability distribution with a minimum at 0.7, mode at 0.95, and maximum at 1.3.
- The contribution to the skin-depth modification factor that accounts for the variation in the number of radionuclides with a dose-rate factor in the plateau region of Fig. 4-3 as the depth of radiosensitive tissues ranges from 4 to 16 mg cm^{-2}, relative to the number of radionuclides with a dose-rate factor in the plateau region at a depth of 7 mg cm^{-2}, can be represented by a uniform probability distribution between 0.8 and 1.1.
- By combining the probability distributions of the two contributions described above, assuming that they are perfectly positively correlated, the skin-depth modification factor (*SDMF*) at a nominal depth of 8 mg cm^{-2} can be represented by a triangular probability distribution with a minimum at 0.5, mode at 0.9, and maximum at 1.5 (Table 4-2).

4.6.1.2.3 *Skin-depth modification factor at nominal depth of 40 mg cm^{-2}*

In some regions of the body, such as the palms of the hands and soles of the feet, radiosensitive tissues in the basal layer of skin are located at an average depth of 40 mg cm^{-2}. The horny pads of the palms and soles can have a thickness of about 60 mg cm^{-2}, whereas the thickness of the epidermis in other areas can be as low as 16 mg cm^{-2} (Whitton 1973; Fig. 6). Dermal contamination of these regions by descending or resuspended fallout may not be as important as contamination by other means, given that handling of contaminated soil or objects can transfer substantial amounts of material to the palms of the hands and the presence of soil particles in boots can lead to significant contamination of soles of the feet.

We assume that 40 mg cm^{-2} is a reasonable central estimate of the depth of radiosensitive tissues in regions of the body where the nominal value is assumed to apply, and that the depth in those regions ranges from 16 to 60 mg cm^{-2}. Using data in Table 1 of Kocher and Eckerman (1987) and Fig. 4-3, the approach to estimating a skin-depth modification factor (*SDMF*) described in Section 4.6.1.2.1 leads to the following results at a nominal depth of 40 mg cm^{-2}:

- The contribution to the skin-depth modification factor that accounts for the variation in the dose-rate factor for higher-energy beta emitters in the plateau region of Fig. 4-3 as the depth of radiosensitive tissues ranges from 16 to 60 mg cm^{-2}, relative to the dose-rate factor in the plateau region at a depth of 7 mg cm^{-2}, can be represented by a triangular probability distribution with a minimum at 0.3, mode at 0.5, and maximum at 0.7.

- The contribution to the skin-depth modification factor that accounts for the variation in the number of radionuclides with a dose-rate factor in the plateau region of Fig. 4-3 as the depth of radiosensitive tissues ranges from 16 to 60 mg cm^{-2}, relative to the number of radionuclides with a dose-rate factor in the plateau region at a depth of 7 mg cm^{-2}, can be represented by a uniform probability distribution between 0.3 and 0.8.

- By combining the probability distributions of the two contributions described above, assuming that they are perfectly positively correlated, the skin-depth modification factor (*SDMF*) at a nominal depth of 40 mg cm^{-2} can be represented by a triangular probability distribution with a minimum at 0.08, mode at 0.3, and maximum at 0.6 (Table 4-2).

4.6.2 Dose-Rate Factors for Alpha-Emitting Radionuclides

In contrast to beta-emitting radionuclides, only a few alpha-emitting radionuclides in fallout from a nuclear weapon detonation are potentially important contributors to doses to skin from dermal contamination. Therefore, it is practical to use radionuclide-specific dose-rate factors for alpha emitters, rather than an approach that would be based on development of nominal dose-rate factors that apply to all alpha emitters in fallout combined.[22]

[22] An important consideration that discourages an approach to estimating doses to skin based on development of nominal dose-rate factors that apply to all alpha-emitting radionuclides in fallout combined is the much stronger energy dependence of dose-rate factors for alpha particles at a given depth in tissue compared with the energy dependence for electrons. The stronger energy dependence, and the resulting lack of a plateau region in the dose-rate factor as a function of energy similar to the plateau regions indicated in Fig. 4-3, is a consequence of the much shorter ranges of alpha particles in tissue and similarities between those ranges and the depths of radiosensitive cells in the basal layer. As indicated by radionuclide-specific dose-rate factors given in Table 4-4, dose-rate factors for mixtures of alpha emitters in fallout generally would not be well represented by a single nominal value.

The model used in this report to calculate dose-rate factors for alpha-emitting radionuclides on the body surface was developed by Eatough (1997). The equivalent dose[23] as a function of depth x in tissue per unit concentration of a radionuclide on the body surface is calculated by numerical integration of stopping powers (energy loss per unit distance of travel) of emitted alpha particles. Eatough (1997) represented the calculated depth-dose distribution by a function containing exponential and linear terms of the form:

$$DRF_{skin}(x) = 2.8 \cdot \frac{E}{R} \cdot [\, e^{-13x/R} + 1 - (x/R)\,] \tag{4-5}$$

where

DRF_{skin} = dose-rate factor at assumed depth of radiosensitive tissues for radionuclide deposited on skin (μSv s^{-1} per Bq cm^{-2});[24]

x = depth in tissue (mg cm^{-2});

E = energy of emitted alpha particle (MeV);

R = range of emitted alpha particle in tissue (mg cm^{-2}).

The exponential term in this model is negligible at depths greater than about 1 mg cm^{-2}.

Equation (4-5) gives the dose-rate factor at a fixed depth x below the body surface (e.g., at the base of the epidermis where the basal layer begins). However, the location of radiosensitive tissues within the finite thickness of the basal layer is uncertain and, as described in Section 4.6.1.2, the thickness of the epidermis in particular regions of the body is variable.

Eatough (1997) addressed the uncertainty in the location of radiosensitive tissues by assuming that they are uniformly distributed in a basal layer of thickness 0.88 mg cm^{-2} in all regions of the body. The mean dose to the basal layer for a given thickness of the epidermis then can be estimated by integrating eq. (4-5) over the assumed thickness of the basal layer.

Eatough (1997) addressed the more important variability in the thickness of the epidermis in particular regions of the body on the basis of various measurements of epidermal thickness

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[23] Equivalent doses are calculated by assuming a radiation weighting factor (w_R) of 20 for alpha particles. The assumed w_R is appropriate when induction of skin cancer is the health effect of concern but would be result in an overestimate of the biologically significant dose when deterministic effects are of concern.

[24] The dose-rate factor in this equation and in eq. (4-6) is expressed in units used by Eatough (1997). To convert to units of rem h^{-1} per μCi cm^{-2} used in this report, dose-rate factors calculated using these equations should be multiplied by 1.33×10^4.

reported in the literature. These data were used to define step-function distributions of epidermal thickness in particular regions of the body, which then were represented by smooth functions to facilitate estimation of a mean dose to the basal layer in those regions. Using this approach, Eatough (1997) calculated mean doses to the basal layer as $\int_0^R D(x)P(x)\,\mathrm{d}x$, where $D(x)$ is given by eq. (4-5) and $P(x)$ is the assumed representation of the distribution of epidermal thickness in a region of interest. The resulting mean dose-rate factor in the basal layer is given by:

$$DRF_{skin} = 2.8 \cdot \frac{E}{R^2} \cdot x_0 \cdot [(2 - f)e^f - (2 + f)] \tag{4-6}$$

$$f = [q - (R + t)]/x_0$$

where t is half the thickness of the basal layer (0.44 mg cm^{-2}), x_0 and q are parameters in the smooth function that was fit to the step-function distributions of epidermal thickness in specific regions of the body, R must be greater than $q - t$, and $q - t$ must be greater than 1 mg cm^{-2}.

Values of q and x_0 in eq. (4-6) depend on the particular source of data used to define distributions of epidermal thickness in specific regions of the body. When the more comprehensive data reported by Whitton (1973) were used, the following values of these parameters in different regions were obtained:

- Back of hand: q = 5, x_0 = 2.4;
- Arms and legs: q = 3.1, x_0 = 2.0;
- Trunk: q = 2.0, x_0 = 1.35;
- Face: q = 1.4, x_0 = 2.1.

On the basis of the model and parameter values described above, the mean dose to the basal layer generally is higher than the dose at the base of the epidermis, due to the increase in stopping power as an alpha particle that can penetrate through the basal layer loses energy in traversing that layer.

Dose-rate factors for selected alpha-emitting radionuclides of potential importance in fallout from a nuclear weapon that we calculated using the model in eq. (4-6) and values of q and x_0 listed above are given in Table 4-4. The mean alpha energy per decay of each radionuclide was obtained from Kocher (1980), and the range in tissue was obtained by linear interpolation of

ranges in “muscle-equivalent liquid (with sucrose)” tabulated by ICRU (1993). The average thickness of the epidermis is about 6.6 mg cm^{-2} on the arms and legs, 4.7 mg cm^{-2} on the trunk, 5.5 mg cm^{-2} on the face, and 9.3 mg cm^{-2} on the back of the hands. Dose-rate factors in other regions can be obtained on the basis of a similarity in the thickness of the epidermis.

The model developed by Eatough (1997) and the dose-rate factors in Table 4-4 do not account for absorption of alpha particles by radioactive particles on the body surface. The range of a 6-MeV alpha particle in a fallout particle at NTS with a density of 2.7 g cm^{-3} is about 30 μm (ICRU 1993); this energy is about the same as the highest energy of alpha particles emitted by radionuclides listed in Table 4-4. For ^{239}Pu, which is the most important alpha emitter in fallout, the energy of alpha particles is about 5.2 MeV, and the range in fallout particles at NTS is about 20 μm. A range of 20 to 30 μm is roughly comparable to diameters of most fallout particles that are retained on the body surface, which are about 50 μm or less (Section 4.2.1).

In developing a representation of the effect of shielding by fallout particles on reducing doses from alpha-emitting radionuclides on the body surface, the following factors were considered: (1) radionuclides of interest in fallout generally are assumed to be isotopes of refractory elements that should be preferentially distributed in the volume of particles (Hicks 1982; Section IV.C.2.1.2 of NRC 2003); (2) alpha particles do not need to be fully absorbed in fallout particles for the dose to the basal layer of skin to be reduced to zero; (3) the shielding required to reduce the dose to zero depends on the thickness of the epidermis; and (4) particles of all sizes up to about 50 μm would be retained on skin. Data on ranges of alpha particles in fallout particles and tissue (ICRU 1993) indicate that shielding by fallout particles could be minimal in cases of deposition of the smallest particles in regions of the body where the epidermis is relatively thin, but shielding could be quite effective in reducing doses in regions where the epidermis is relatively thick. Rather than developing probability distributions of shielding factors for specific regions of the body with different thicknesses of the epidermis, which is difficult to justify when shapes of fallout particles are irregular and distributions of alpha-emitting radionuclides in fallout particles are uncertain, we define a single probability distribution that would apply in any region of the body.

On the basis of the considerations described above, we assume that the effect of shielding by fallout particles is a reduction of dose-rate factors for alpha-emitting radionuclides given in

Table 4-4 by a multiplicative factor that is represented by a log-uniform probability distribution with a minimum at 0.05 and maximum at 1.0. The mean and median of this distribution are about 0.3 and 0.2, respectively; i.e., on average, shielding by fallout particles is assumed to reduce doses from dermal contamination by alpha-emitting radionuclides by a factor of about three. The assumed effect of shielding for alpha particles is substantially greater than the effect of shielding for electrons discussed in Section 4.6.1.1, which is an expected result. Given the dependence of dose-rate factors on the thickness of the epidermis, we believe that the assumed probability distribution of the shielding factor should underestimate the effect of shielding by fallout particles in reducing doses in many regions of the body.

When alpha particles emitted by a radionuclide are sufficiently energetic to irradiate the entire thickness of the basal layer, the dose-rate factor is much higher than the dose-rate factor for a beta-emitting radionuclide; the increase is about three orders of magnitude or more in some cases. The much higher dose-rate factors for alpha emitters are due to a combination of the much shorter range (higher stopping power) of alpha particles in tissue, the assumed radiation weighting factor (w_R) of 20 for alpha particles, and the higher energy of emitted alpha particles compared with average beta energies. Thus, relatively low activity concentrations of alpha emitters on the body surface, compared with concentrations of beta emitters, can result in relatively high doses to the basal layer.[25]

As discussed in Section 4.6.1.2, there are regions of the body, such as the palms of the hands and soles of the feet, where the average thickness of the epidermis is about 40 mg cm^{-2}. Alpha particles emitted by radionuclides are not sufficiently energetic to penetrate the epidermis in those regions.

Uncertainties in dose-rate factors for alpha-emitting radionuclides in Table 4-4 are difficult to assess on the basis of available information. The sensitivity of the dose-rate factor for a given radionuclide to the assumed thickness of the epidermis, as indicated by comparisons of

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[25] Since data on concentrations of plutonium in fallout are classified, we could not investigate the potential importance of doses to skin from dermal contamination by alpha-emitting radionuclides in fallout compared with doses from beta emitters. At times shortly after a detonation when concentrations of shorter-lived beta emitters in fallout are high, calculations performed by SAIC (personal communication from J. Stiver) indicated that doses from alpha emitters should be unimportant. Given the long half-lives of the important isotopes of plutonium, the ratio of the dose to skin from alpha emitters to the dose from beta emitters should increase as the time after detonation increases to several years.

dose-rate factors for higher-energy alpha emitters on the arms and legs and on the trunk, suggests that the uncertainty is substantial. We believe that an uncertainty of a factor of three is reasonable. This uncertainty can be represented by a multiplicative factor in the form of a lognormal probability distribution with a GM at 1.0 and 90% CI of (0.33, 3).[26]

4.7 Efficiency of Showering

In Section 3.5, models to estimate dose to skin from exposure to radionuclides on the body surface were developed that account for incomplete removal of contamination by showering or washing. The effect of inefficient showering is represented by two parameters that are assumed to describe independent processes for removal of contamination from skin. The first parameter, denoted by β, describes the fraction of contamination that is removed by exfoliation of skin cells while showering. This parameter is assumed to be the same in each shower, and exfoliation of skin cells by other processes (i.e., between showers) is assumed to be taken into account implicitly. The second parameter, denoted by γ_j, describes the fraction of the contamination that is removed by washing during the *j*th shower after a deposition on skin. Removal by washing is assumed to be less efficient in each of the first few showers, as residual contamination becomes more embedded in skin folds and pores.

By assuming that an individual showers once per day, the fraction of the contamination on skin that is removed during the *j*th shower is estimated as $(\gamma_j + \beta)$. The fraction of the contamination on skin at the time of the *j*th shower that remains after that shower, denoted by α_j, then is estimated as $\alpha_j = 1 - (\gamma_j + \beta)$. The parameter α_j applies to the amount of contamination on skin at the time of the *j*th shower, not the amount at the time of the first shower after deposition on skin occurs.

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[26] An uncertainty in data used to develop the radiation weighting factor (w_R) of 20 for alpha particles is not taken into account in the assumed uncertainty in dose-rate factors for alpha-emitting radionuclides. Uncertainty in the biological effectiveness of alpha particles in inducing cancer in humans relative to high-energy photons is taken into account in the probability distribution of the radiation effectiveness factor (REF) for alpha particles that is incorporated in the computer code that calculates the probability of causation/assigned share (PC/AS) of a diagnosed cancer in an individual associated with a given alpha dose to a specific organ or tissue (Land et al. 2003; Kocher et al. 2008).

Recommended values of the parameters β and α_j and their uncertainties are discussed in the following sections.

4.7.1 Removal of Radionuclides from Skin by Exfoliation of Skin Cells

Limited data on removal times for cells in the epidermis reported in ICRP Publication 23 (ICRP 1975) are given in Appendix D.2.1. On the basis of those data, we assume the following nominal turnover times of skin cells by exfoliation:

Upper limbs, 20 days;
Lower limbs, 30 days;
Abdomen, 40 days;
Scalp, 120 days.

The cell turnover time on the abdomen is assumed to apply in all regions of the trunk.

By assuming that an individual showers once each day, the fraction of the activity of radionuclides on skin that is removed by exfoliation of skin cells in each shower, β, is numerically equal to the reciprocal of the turnover time for skin cells in days. As noted above, β also takes into account exfoliation of skin cells between showers. When the same fraction removed is assumed to apply to the amount of contamination present on skin at the time of each shower, some contamination is assumed to remain on skin after all cells that were present at the time of deposition are removed by exfoliation.

Given the paucity of data on ranges of turnover times for skin cells (Appendix D.2.1), assumptions about nominal values of the fraction of contamination removed by exfoliation of skin cells in each daily shower, β, and their uncertainties are largely a matter of judgment. We assume that the most likely value of this parameter in any region of the body is numerically equal to the reciprocal of the nominal turnover time for skin cells in that region given above, and that the variation from the most likely value should be no more than 50%. In each region of the body specified above, we represent the assumed uncertainty in the parameter β by a symmetrical triangular probability distribution with a mode at the assumed nominal value and minimum and maximum values that differ from the nominal value by 50%. The nominal (deterministic) values and assumed probability distributions of the parameter β are given in Table 4-5.

4.7.2 Removal of Radionuclides from Skin by Showering

Data on the efficiency of washing in removing contamination from skin obtained from several studies are presented and discussed in Appendix D.2.2. Estimates of the fraction of contamination removed by washing in the *j*th shower, γ_j, used in modeling the effect of inefficient showering that were obtained from data reported by Boeniger (2006), Sharp and Chapman (1957), and Friedman (1958) are given in Tables D-2, D-4, and D-7, respectively. Additional data reported by Sharp and Chapman (1957) are summarized in Table D-5, and data reported by Fogh et al. (1999) are discussed in Appendix D.2.2.6.

None of the studies reviewed in Appendix D.2.2 appear to provide definitive estimates of the fraction of contamination removed by washing in the *j*th shower, γ_j, for use in applying models developed in Section 3.5 to estimate doses to skin for military participants at atmospheric nuclear tests. Data on native Marshallese and military personnel who were exposed to fallout from Operation CASTLE, Shot BRAVO in the Pacific reported by Sharp and Chapman (1957) are potentially the most relevant. However, external exposure rates at the body surface, rather than levels of contamination on skin, were measured in that study, and the measurements, especially those after the first shower, probably included significant contributions from internally deposited radionuclides. Concerns about use of data obtained from other studies include that (1) particle sizes may have been substantially smaller than typical particle sizes in contamination on skin of military personnel, (2) methods of removal of contamination from skin, such as use of wipes on dry skin, may not have resembled removal by normal washing, or (3) efforts at removal of contamination may have been more vigorous than in a typical shower. Given the limitations in available data, judgment is required in estimating nominal values of γ_j and their uncertainties, especially in showers after the first ($j \geq 2$) when little of the initial contamination may remain on skin and only a small fraction of the remaining contamination may be removed by washing.

For purposes of estimating dose to skin of military personnel, we define two sets of values of the parameter γ_j and their uncertainties. The first set would be used when normal showering is assumed and no special effort was made to remove radioactive contamination. This set is intended to apply, for example, to military personnel on residence islands in the Pacific who may have been exposed routinely to previously deposited fallout that was resuspended by

winds and normal human activities. The second set would be used when significant contamination of skin is known or strongly suspected, such as in cases of exposure to descending fallout on ships or on land in the Pacific, and there may have been special efforts (e.g., unusually vigorous scrubbing) to remove contamination by showering. Deliberate attempts at removal of contamination are assumed to be more efficient than normal showering.

Two additional assumptions are used in defining removal fractions of contamination by washing and their uncertainties in the two cases of normal and highly efficient showering described above. First, since available data do not permit distinctions in values of γ_j beyond the third shower, γ_j is assumed to be the same for $j \geq 4$. Second, we assume that there is no difference in removal fractions beyond the third shower in the two cases. That is, even when significant contamination of skin is known or strongly suspected, we assume that special efforts to remove contamination by showering would no longer be undertaken when most of the contamination has already been removed. Neither assumption has a pronounced effect on estimated doses to skin when, in each of the two cases, most of the contamination is assumed to be removed in the first three showers.

As in representing uncertainties in removal fractions of contamination by exfoliation of skin cells in the previous section, uncertainties in removal fractions by washing, γ_j, are represented by symmetrical triangular probability distributions. The nominal (deterministic) values and assumed probability distributions for the two cases of normal showering and highly efficient showering in a deliberate effort to remove contamination are given in Table 4-5. In each of the first four showers, washing is assumed to be increasingly less efficient in removing contamination in either case and the uncertainty in the efficiency of showering is assumed to increase. We also note that since the maximum and minimum values of a triangular probability distribution are never sampled when Monte Carlo methods are used to propagate uncertainty, the removal fraction in the first shower (γ_1) when showering is assumed to be highly efficient would always be less than 1.0.

An important consideration in applying uncertain removal fractions by washing, γ_j, in Table 4-5 is the extent to which the removal fraction is correlated from one shower to the next. A strong correlation seems reasonable when it is unlikely that an individual's showering habits or the ability of an individual's skin to retain contamination would change significantly from one

shower to the next. Although the correlation presumably is not perfect in reality, a full correlation between the removal fraction in one shower and the next (correlation coefficient of +1.0) could be justified on the grounds that (1) data on removal of contamination by showering are limited and (2) the uncertainty in the dose to skin due to uncertainty in the efficiency of showering in removing contamination would not be underestimated.

There also could be a positive correlation between the fraction of contamination removed by showering, γ_j, and fraction removed by exfoliation of skin cells, β. Such a correlation would take into account that both removal fractions should be higher in more vigorous showers and lower in less vigorous showers. However, a correlation between the two removal fractions is not included in our analysis, on the grounds that β also is intended to take into account removal of contamination by exfoliation of skin cells between showers, which would be unrelated to exfoliation by showering, and the relative importance of exfoliation while showering and between showers is unknown. Although it would be reasonable to assume a partial positive correlation between the two removal fractions, the effect on the uncertainty in an estimate of the effect of inefficient showering on doses to skin should be small compared with the uncertainty when the two removal fractions are assumed to be uncorrelated.

4.7.3 Calculations to Investigate Effects of Inefficient Showering

When a single shower does not remove all contamination on the body surface, the dose to skin after the first shower, D_{sh}, due to residual contamination from a single deposition event can be calculated using eq. (3-35) if deposition is acute (e.g., exposure to descending fallout) or eq. (3-37) if deposition is continuous (e.g., exposure to fallout resuspended by winds). Those equations have identical structures and give D_{sh} for a known activity concentration of radionuclides on skin at the time a deposition event ceased. For an acute deposition, the entire activity concentration on skin $C_{skin}(T_0)$ is assumed to be deposited at time T_0 after a detonation, whereas for a continuous deposition, the activity concentration on skin increases from zero at time T_0 and to a value $C_{skin}(T_{dep})$ at the time T_{dep} when deposition ceased.

This section presents results of calculations to investigate the effect of variations in model parameters on D_{sh} and its importance relative to the dose to the time of the first shower, D_1. A unit activity concentration of radionuclides in fallout on the body surface at the time a

deposition event ceased was assumed in all calculations, and the effect of varying the following parameters was investigated: (1) the time after a detonation when deposition ceased (T_0 for an acute deposition or T_{dep} for a continuous deposition), (2) the interval between the time deposition ceased and the time of the first shower (ΔT_{post}), which is referred to in these discussions as the time to the first shower, (3) removal fractions of radionuclides by washing in the first and subsequent showers (γ_j), and (4) the removal fraction of radionuclides by exfoliation of skin cells (β). All results were obtained using eq. (3-35) or (3-37), which apply to mixtures of radionuclides in fallout. The number of showers (N) was assumed to be 120.

Results of calculations shown in Fig. 4-4 illustrate the dependence of the dose to skin after the first shower (D_{sh}) on the time after a detonation when deposition on skin ceased (T_0) in the range from 2 hours to 4 years, the time to the first shower (ΔT_{post}) in the range from 1 to 24 hours, and the efficiency of showering. All calculations assumed deposition on the trunk and deterministic values of removal fractions by exfoliation of skin cells (β) and by normal or highly efficient showering (γ_j) given in Table 4-5. These results indicate the following:

- D_{sh} increases with increasing time after a detonation when deposition ceased (T_0). This effect, which is most pronounced at times T_0 of 6 months or less, is a consequence of the relatively rapid rate of decrease in the activity of all radionuclides in fallout at times shortly after a detonation and the increasingly slower rates of decrease at longer times.

- When deposition on skin ceases at 2 hours after a detonation, D_{sh} decreases by a factor of about three as the time to the first shower (ΔT_{post}) increases from 1 to 24 hours. However, the dependence of D_{sh} on ΔT_{post} is less at longer times after a detonation, and there is very little dependence at times T_0 beyond about 30 days. These effects also are a consequence of the dependence of the rate of decrease in the activity of all radionuclides in fallout on time after a detonation.

- An assumption of highly efficient showering reduces D_{sh} by a factor of about 3 to 4 compared with an assumption of normal showering; this reduction is nearly independent of the time after a detonation when deposition ceased (T_0) and the time to the first shower (ΔT_{post}). The reduction in doses after the first shower is mainly the consequence of an assumption that the activity of radionuclides that remains on skin after the first

three showers when normal showering is assumed is about twice the activity that remains when highly efficient showering is assumed.

The dependence of the dose after the first shower, D_{sh}, on the removal fraction of radionuclides by exfoliation of skin cells (β), which is assumed to depend on the region of the body of interest, is illustrated in Fig. 4-5. At a time to the first shower (ΔT_{post}) of 6 hours, a decrease in β by a factor of about six, as indicated in Table 4-5, results in an increase in D_{sh} that ranges from less than a factor of two at times shortly after a detonation when deposition on skin ceased (T_0) to a factor of about three at longer times. Removal by exfoliation is important compared with removal by showering only after the first few showers.

The importance of the dose after the first shower, D_{sh}, relative to the dose to the time of the first shower, D_1, is illustrated in Figs. 4-6, 4-7, and 4-8. The importance of D_{sh} relative to D_1 depends mainly on three factors: (1) the efficiency of showering, which affects only D_{sh} but not D_1; (2) the time to the first shower, ΔT_{post}; and (3) the time after a detonation when deposition on skin ceased, T_0. If showering is less efficient in removing contamination from skin, the importance of D_{sh} relative to D_1 increases.

Results in Figs. 4-6 and 4-7 illustrate how the importance of the dose after the first shower, D_{sh}, relative to the dose before the first shower, D_1, depends on the time to the first shower, ΔT_{post}, for times after a detonation when deposition on skin ceased, T_0, of 2 hours and 6 months, respectively. These results indicate that D_{sh} is small compared with D_1 only if T_0 is short; at longer times T_0, D_{sh} is much larger than D_1. These results also show that D_1 depends on the time to the first shower, ΔT_{post}, for any value of T_0, whereas D_{sh} changes significantly with an increase in ΔT_{post} only at shorter times after a detonation. For any value of T_0, the importance of D_{sh} relative to D_1 increases with decreasing ΔT_{post}. Differences in these results at times after a detonation when deposition on skin ceased of 2 hours and 6 months also are a consequence of the dependence of the rate of decrease of the activity of all radionuclides in fallout combined on time after a detonation.

In equations presented in Section 3.5 and in results shown in Figs. 4-6 and 4-7, D_1 represents the dose from the time deposition on skin ceased until the time of the first shower. This dose, which is denoted by D_{post} in equations to estimate doses due to resuspension of previously deposited fallout by human activities in Section 3.3.2, is the only dose received before

the first shower when deposition is modeled as an acute event. However, when a deposition event is modeled as a continuous process, an additional dose D_{dep} is received during the period of deposition, as indicated in eq. (3-36) in Section 3.5.3. Figure 4-8 shows results of calculations that are the same as those in Fig. 4-7, except continuous deposition onto skin for a period of 4 hours, resulting in an additional dose D_{dep} before the time of the first shower, is assumed. A comparison of results in Figs. 4-7 and 4-8 indicates that the main effect of the additional dose D_{dep} in this case is to increase the dose to the time of the first shower, with the largest increases occurring at times to the first shower, ΔT_{post}, of about 6 h or less. The ratio of the dose after the first shower, D_{sh}, to the dose before the first shower is reduced accordingly.

Results of example calculations of uncertainties in the dose to skin after the first shower, D_{sh}, assuming deposition on the trunk and a time to the first shower, ΔT_{post}, of 6 hours, are shown in Fig. 4-9. For a unit activity concentration of radionuclides in fallout on skin and assuming that the time after a detonation when deposition on skin ceased (T_0) and the times of showers are specified without uncertainty, the uncertainty in D_{sh} is determined by uncertainties in removal fractions of radionuclides by washing (γ_j) and exfoliation of skin cells (β) and the uncertainty in the dose-rate factor. Uncertainties in D_{sh} increase slightly as the time T_0 increases and are smaller for normal showering than for highly efficient showering. The latter effect is a consequence of the assumption indicated in Table 4-5 that the uncertainty in the fraction of the activity of radionuclides that remains on skin after each shower, $\alpha_j = 1 - (\gamma_j + \beta)$, is somewhat smaller for normal showering than for highly efficient showering. The dominant source of uncertainty in D_{sh} is the uncertainty in the fraction removed by washing, γ_j.

In calculating probability distributions of D_{sh} using random sampling from probability distributions of model parameters, it is important to recognize that when probability distributions in Table 4-5 are assumed, the sum of sampled values of γ_1 (the removal fraction by washing in the first shower) and β (the removal fraction by exfoliation of skin cells) could be greater than 1.0, which would result in a negative value of the fraction of the activity of radionuclides that remains on the body surface after the first shower, $\alpha_1 = 1 - (\gamma_1 + \beta)$. In such cases, which would be most common when highly efficient showering is assumed, α_1 should be set to zero. When probability distributions in Table 4-5 are assumed, negative values of α_j would not be generated by random sampling for any shower after the first.

4.8 Additional Discussions

The previous sections have discussed an approach to estimating doses to skin from deposition of airborne radioactive fallout particles on bare skin. Deposition on skin under clothing also can occur by circulation of contaminated air under clothing. However, clothing acts as a filter that allows fewer particles to impact skin over much of the body. Filtration by clothing presumably depends on the type and thickness of clothing. Filtration probably is efficient for medium and large particles but not so efficient for very small particles. If we assume that clothing was worn loosely, which probably was the case in the warm environment of the Pacific, it would be reasonable to calculate doses to skin by ignoring filtration by clothing. At NTS, many veterans participated in simulated war exercises while wearing combat uniforms. In these cases, it is likely that only a fraction of fallout particles incident on an individual penetrated through clothing to impact skin. However, we are not aware of any information about the magnitude of such an effect.

In addition to direct deposition on skin under clothing, a potentially important effect is deposition of soil particles on clothing. Many radionuclides emit electrons of sufficient energy to penetrate through normal clothing and reach radiosensitive tissues in the basal layer of skin. Doses from contamination of clothing are discussed in Section 5. Clothing is assumed to be completely effective in shielding alpha particles emitted by radionuclides.

Models and parameter values described in Sections 3 and 4 are used to estimate doses to skin due to deposition of radionuclides in particulate material on bare skin. When using these models, the following considerations should be kept in mind:

- The fraction of the mass of airborne material incident on the body surface that is intercepted and retained on skin, *r*, is expected to be less than 1.0 in most regions of the body. That is, the concentration of airborne material that is intercepted and retained on skin in most regions of the body will be less than the concentration of material that is deposited on the ground surface during the time exposure to airborne material occurs.

- In special cases, such as accumulation of soil particles on the back of the neck under a collar, under the belt, on the shin under the edge of boots, or behind the ears, the

- The amount of material assumed to be deposited on skin should not exceed a reasonable upper bound of possible soil loadings. Sheppard and Evenden (1994) observed soil loadings on skin due to direct contact of 2 to 6 mg_{soil} per cm^2_{skin} when soil was moist. However, at concentrations above 2 mg_{soil} per cm^2_{skin}, dirt is visible on skin, and it is likely that brushing or cleaning would take place soon after contamination. Thus, if information is available, it may be desirable in some cases to verify that the soil loading does not exceed a maximum credible value before using eq. (3-1). Since that equation is expressed in terms of the activity concentration of material on skin ($\mu Ci\ cm^{-2}_{skin}$), the soil loading must be estimated using a specific activity of particles that accumulate on skin ($\mu Ci\ mg^{-1}_{soil}$), a quantity that is not always available in most situations involving exposure of military personnel. A reasonable maximum soil loading on skin can be an important concern in some exposure scenarios, such as exposure by direct contact with contaminated soil, exposure of forward observers to all previously deposited fallout that was resuspended by the blast wave in a nuclear detonation at NTS, or exposure to fallout that was resuspended by other vigorous stressors (e.g., helicopter landing or takeoff) that resulted in unusually high dust loadings in air. When maximum soil loadings occur, it could be reasonable to assume a relatively short time before the first washing and a high removal efficiency in the first washing in estimating doses to skin.

Table 4-1. Interception and retention fractions estimated from data obtained in CENIZA-ARENA volcanic ash studies in Costa Rica

Body region or area	Interception and retention fraction (r)[a]			Comment
	Deterministic value[b]	Uncertainty distribution[c]	90% credibility interval (CI)	
Face, shoulders, back and sides of torso, forehead, palms	0.015	LN (0.015, 3.6)	0.002–0.12	Little or no hair
Chest (unspecified amount of hair)	0.03	LN (0.03, 3.9)	0.003–0.28	Amount of hair from little to abundant
Forearms, upper legs, lower legs (above boot edge)	0.06	LN (0.06, 3.0)	0.01–0.36	Hair-covered areas
Scalp	0.23	LN (0.23, 2.45)	0.053–1.0	
Back of neck under collar, under belt, under boot edge, behind ears	1.5	Γ (0.04, 1.2, 5)	0.04–5.0	Special regions[d]

[a] Interception and retention fraction is unitless ratio of mass of volcanic ash per unit area deposited and retained on skin in defined regions of the body to time-integrated mass of volcanic ash deposited per unit area on the ground. Values normally are less than 1.0, except at noted in footnote d.

[b] Point estimates of parameters recommended for use in estimating deterministic values of dose to skin from dermal contamination. Values are used in Section 6 to investigate importance of doses to skin from dermal contamination.

[c] LN = Lognormal (median, geometric standard deviation); Γ = Gamma (5^{th} percentile, 50^{th} percentile, 95^{th} percentile).

[d] In special regions of the body, material deposited in other regions can migrate and accumulate, and interception and retention fraction can be greater than 1.0 (see Section 4.1.5).

Table 4-2. Summary of parameter values used to estimate electron doses to skin from dermal contamination

Parameter	Symbol	Unit	Deterministic value[a]	Uncertainty distribution[b]
Interception and retention fraction	$r = (a_h/s)$		See Table 4-1	
Particle-size adjustment	PS_a	unitless		
Small particles[c]			1.3	LN (1.3, 1.1)
Large particles[d]			0.8	T (0.4, 0.8, 1.0)
Unknown particle sizes[e]			1.0	U (0.4, 1.6)
Enhancement due to moisture	EM	unitless		
Pacific Proving Ground			1.15	U (0.8, 1.5)
Nevada Test Site			0.75	U (0.5, 1.0)
Enrichment of specific activity	EF	unitless		
Small particles[c]			1.3	T (1.0, 1.0, 2.0)
Large particles[d]			2.5	T (1.0, 2.5, 4.0)
Unknown particle sizes[e]			2.0	LU (1.0, 4.0)
Activity-weight adjustment factor	AW	unitless		
Small particles[c]			1	T (0.7, 1.0, 1.0)
Large particles[d]			0.03	LN (0.032, 2.0)
Unknown particle sizes[e]			0.1	LT (0.01, 0.1, 1.0)
Deposition velocity	V_D	m s^{-1}	1.0	T (0.5, 1.0, 3.0)
Wind speed	V_W	m s^{-1}		
Pacific Proving Ground			5.0	U (3.0, 7.0)
Nevada Test Site			4.0	U (2.0, 6.0)
Dose-rate factor at depth in tissue of 7 mg cm^{-2}	DRF	rem h^{-1} per μCi cm^{-2}	3.7	T (1.6, 3.7, 6.8)
Skin-depth modification factor	$SDMF$	unitless		
Face, forehead, neck, shoulders, torso, upper legs			1.3	T (0.7, 1.3, 1.7)
Forearms, lower legs			0.9	T (0.5, 0.9, 1.5)
Palms of hands, soles of feet			0.3	T (0.08, 0.3, 0.6)

[a] Point estimates of parameters recommended for use in estimating deterministic values of dose to skin from dermal contamination. Values are used in Section 6 to investigate importance of doses to skin from dermal contamination.

[b] LN = Lognormal (median, geometric standard deviation); T = Triangular (minimum, mode, maximum); U = Uniform (minimum, maximum); LU = Log-uniform (minimum, maximum); LT = Log-triangular (minimum, mode, maximum).

[c] Term "small particles" refers to size distributions in which most particles have diameters < 100 μm and median diameter is < 50 μm. Parameter values for small particles are applicable, for example, to exposures far from ground zero in the Pacific or to exposures in cases of resuspension by winds or other mild stresses.

[d] Term "large particles" refers to size distributions in which most particles have diameters > 50 μm and median diameter is > 100 μm. Parameter values for large particles are applicable, for example, to exposures of forward observers in blast-wave region of nuclear detonations at NTS that occur within the first few minutes.

[e] Parameter values for unknown particle sizes are not intended to be used when substantial fractions of the activity of radionuclides were carried by small and large particles and those fractions can be estimated (see Section 4.2.5).

Table 4-3. Summary of resuspension factors (RF, m^{-1}) used to estimate airborne concentrations of radionuclides due to resuspension of radionuclides deposited on ground surface

Resuspension scenario	Deterministic value[a]	Uncertainty distribution: Probability distribution[b]	Uncertainty distribution: 90% credibility interval (CI)
Human activities			
Vehicular traffic	2×10^{-5}	LN (2×10^{-5}, 11)	4×10^{-7} to 10^{-3} m^{-1}
Helicopter take-off or landing	1×10^{-3}	LN (10^{-3}, 4)	10^{-4} to 10^{-2} m^{-1}
Walking – 0.3 m above ground	2×10^{-5}	LN (2×10^{-5}, 5.7)	10^{-6} to 3×10^{-4} m^{-1}
Walking – 1 m above ground	1×10^{-7}	LN (1×10^{-7}, 6.2)	10^{-8} to 2×10^{-6} m^{-1}
Wind-driven resuspension			
Up to about 6 months after deposition	1×10^{-6}	LN (10^{-6}, 16)	10^{-8} to 10^{-4} m^{-1}
Years after deposition	3×10^{-8}	LN (3×10^{-8}, 33)	10^{-10} to 10^{-5} m^{-1}
Detonations at NTS[c]			
Forward observers in blast-wave region at time of detonation; exposure to large particles only[d]	1×10^{-5}	LN (10^{-5}, 16)	10^{-7} to 10^{-3} m^{-1}
Participants in blast-wave region at times after detonation; exposure to small particles only[e]	1×10^{-7}	LN (10^{-7}, 67)	10^{-10} to 10^{-4} m^{-1}
Participants who entered thermal-pulse region after detonation; exposure to small particles only[f]	1×10^{-5}	LN (10^{-5}, 16)	10^{-7} to 10^{-3} m^{-1}

[a] Point estimates of parameters recommended for use in estimating deterministic values of dose to skin from dermal contamination. Values are used in Section 6 to investigate importance of doses to skin from dermal contamination.

[b] LN = Lognormal (median, geometric standard deviation).

[c] Thermal-pulse and blast-wave regions near ground zero of nuclear detonations at NTS are described in Section 4.3.3.

[d] Resuspension factor is used in estimating dermal contamination due to redeposition of large particles that fell to Earth within a few minutes after a detonation (see Sections 3.3.4 and 4.3.3).

[e] Resuspension factor is used in estimating dermal contamination due to redeposition of small particles at times after large particles fell to Earth (see Sections 3.3.4 and 4.3.3). Resuspension factor applies to forward observers who remained in blast-wave region for some time after detonation and to observers or maneuver troops who entered blast-wave within a few hours after detonation.

[f] Participants entered thermal-pulse region only at times after large resuspended particles in that region fell to Earth, when only small particles remained airborne.

Table 4-4. Dose-rate factors for selected alpha-emitting radionuclides deposited on skin in specific regions of the body[a]

Radionuclide[b]	Dose-rate factor[c,d] (rem h^{-1} per $\mu Ci\ cm^{-2}$)	Radionuclide[b]	Dose-rate factor[c,d] (rem h^{-1} per $\mu Ci\ cm^{-2}$)
Arms and legs			
^{235}U	6.9×10^{1}	$^{239,240}Pu$	7.4×10^{2}
^{238}U	1.1×10^{1}	^{241}Am	1.3×10^{3}
^{238}Pu	1.3×10^{3}	^{242}Cm	2.9×10^{3}
Trunk			
^{235}U	3.2×10^{3}	$^{239,240}Pu$	6.7×10^{3}
^{238}U	2.5×10^{3}	^{241}Am	8.2×10^{3}
^{238}Pu	8.2×10^{3}	^{242}Cm	1.1×10^{4}
Face			
^{235}U	4.0×10^{3}	$^{239,240}Pu$	6.4×10^{3}
^{238}U	3.2×10^{3}	^{241}Am	7.4×10^{3}
^{238}Pu	7.4×10^{3}	^{242}Cm	9.6×10^{3}
Back of hand			
^{242}Cm	4.3×10^{1}	Others	0
Palm of hand, sole of foot			
All alpha emitters	0		

[a] Dose is mean equivalent dose to basal layer of skin. Dose-rate factors were calculated using model developed by Eatough (1997) [see eq. (4-6)] and distributions of epidermal thickness in different regions of the body reported by Whitton (1973).

[b] Radionuclides listed are most important alpha emitters in fallout from nuclear weapon detonations.

[c] Uncertainty in calculated dose-rate factors can be described using a multiplicative factor represented by a lognormal probability distribution with a GM at 1.0 and 90% CI of (0.33, 3).

[d] Values do not account for reductions in dose rate due to shielding by particles to which alpha-emitting radionuclides are attached. Shielding by particles could reduce dose rates from alpha particles by factor represented by log-uniform probability distribution between 0.05 and 1.0; this distribution has a mean at about 0.3 and median at about 0.2 (see Section 4.6.2).

Table 4-5. Summary of values of parameters used to model effect of inefficient showering on doses to skin from dermal contamination[a]

Parameter	Deterministic value[b]	Uncertainty distribution	
		Probability distribution[c]	90% credibility interval (CI)
Fraction removed by exfoliation of skin cells per shower (β; unitless)			
Upper limbs	0.05	T (0.025, 0.05, 0.075)	(0.033, 0.067)
Lower limbs	0.033	T (0.017, 0.033, 0.050)	(0.022, 0.045)
Trunk	0.025	T (0.012, 0.025, 0.038)	(0.016. 0.034)
Scalp	0.0083	T (0.0041, 0.0083, 0.013)	(0.0055, 0.012)
Fraction removed by washing per shower (γ_j; unitless)			
Normal showering[d]			
1st shower	0.7	T (0.45, 0.7, 0.95)	(0.53, 0.87)
2nd shower	0.35	T (0.2, 0.35, 0.5)	(0.25, 0.45)
3rd shower	0.1	T (0.05, 0.1, 0.15)	(0.066, 0.13)
≥ 4th shower	0.02	T (0.005, 0.02, 0.035)	(0.01, 0.03)
Highly efficient showering[e]			
1st shower	0.85	T (0.7, 0.85, 1)	(0.75, 0.95)
2nd shower	0.6	T (0.4, 0.6, 0.8)	(0.46, 0.74)
3rd shower	0.25	T (0.1, 0.25, 0.4)	(0.15, 0.35)
≥ 4th shower	0.02	T (0.005, 0.02, 0.035)	(0.01, 0.03)

[a] Models are described in Section 3.5 and assumptions about parameters are discussed in Sections 4.7.1 and 4.7.2.

[b] Point estimates of parameters recommended for use in estimating deterministic values of dose to skin from dermal contamination.

[c] T = triangular (minimum, mode, maximum).

[d] Values apply when it is assumed that special efforts to remove radioactive contamination from skin would not be made.

[e] Values apply when it is assumed that significant radioactive contamination of skin is known or strongly suspected and special efforts would be made to remove contamination while showering.

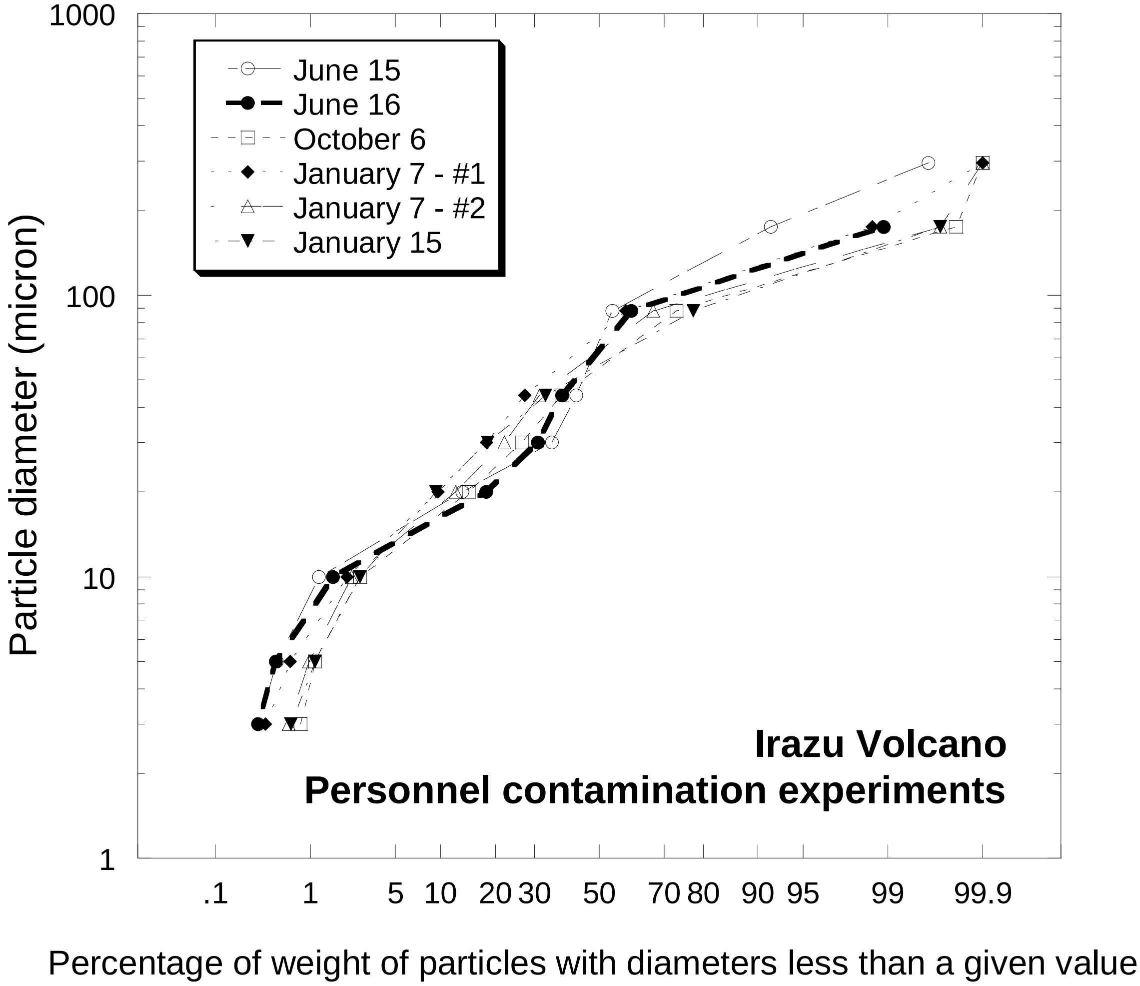

Figure 4-1. Cumulative weight distributions of volcanic ash particles in personnel contamination studies during eruption of Irazu Volcano in Costa Rica (Miller 1966b).

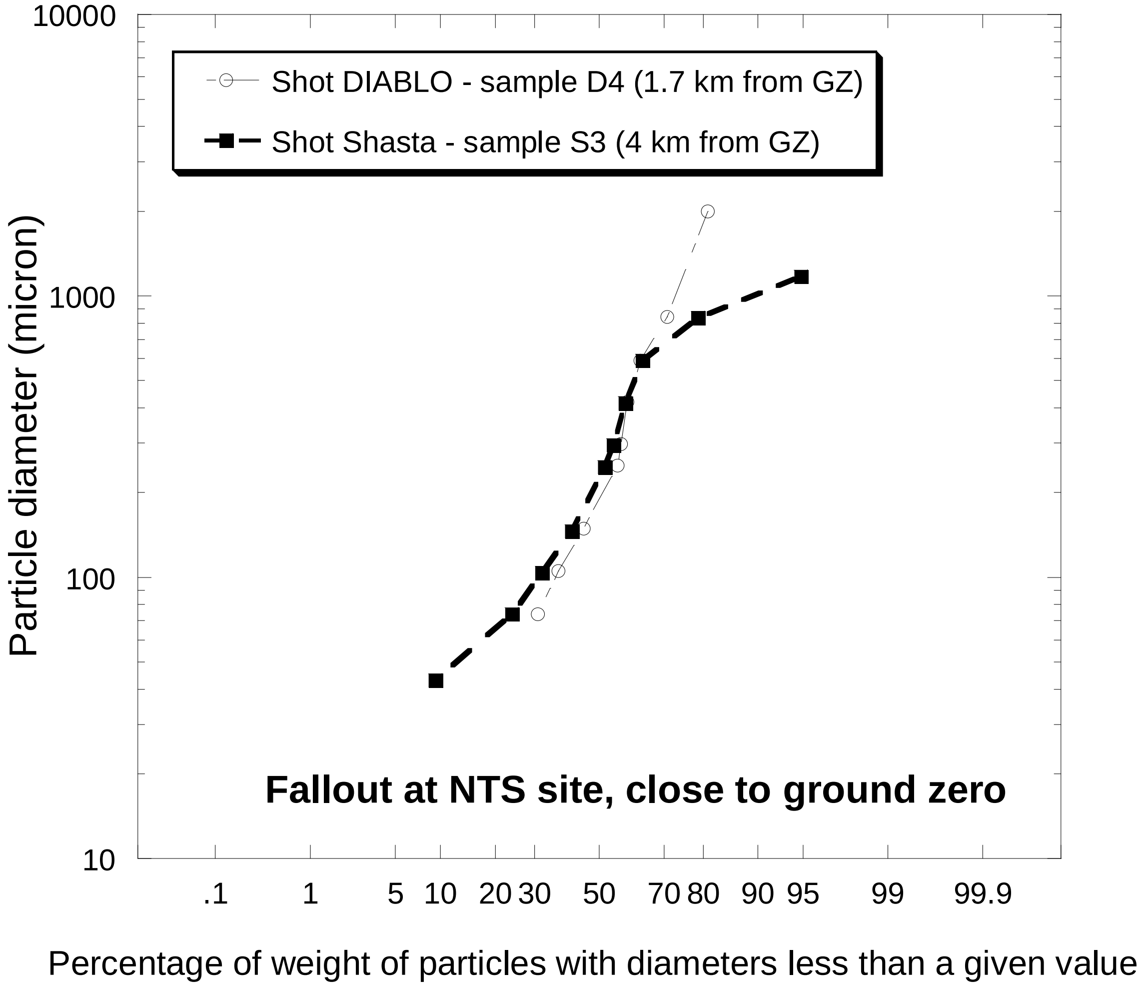

Figure 4-2. Cumulative weight distributions of particles in fallout at NTS (Miller, 1969; data at Shot DIABLO from Table 14; data at Shot SHASTA from Table 16 and Fig. 12).

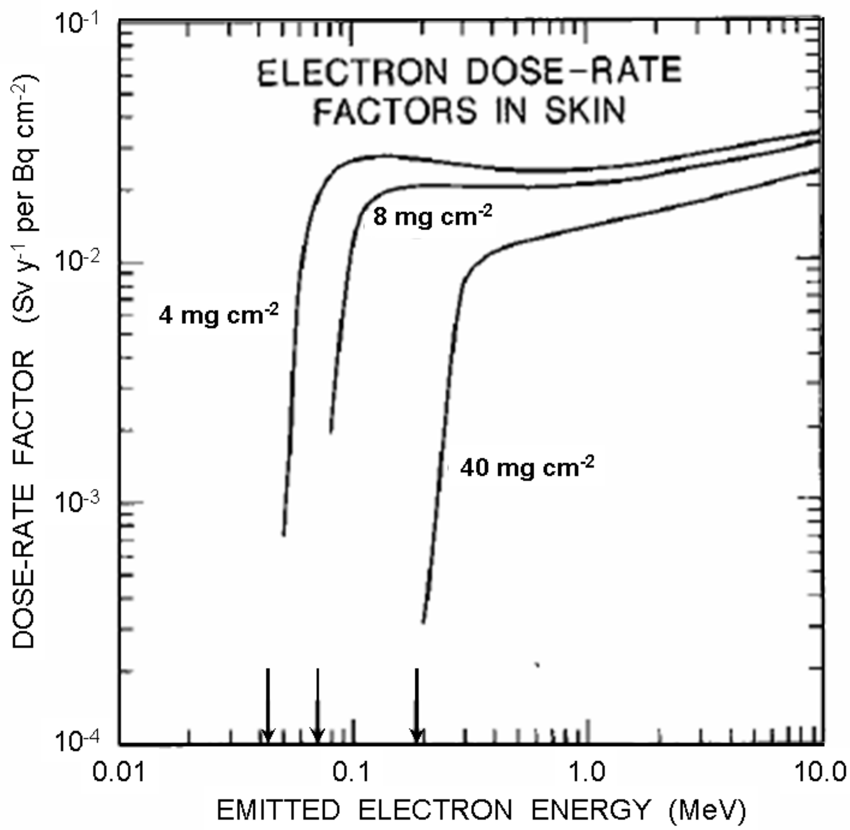

Figure 4-3. Electron dose-rate factors at various depths in skin vs emitted electron energy for monoenergetic sources deposited uniformly on the body surface; arrows at bottom of figure give electron energies below which dose-rate factor at each depth is zero [reproduced from Kocher and Eckerman (1987)]. To convert dose-rate factor to units of rem h^{-1} per μCi cm^{-2} used in this report, multiply values in figure by 423.

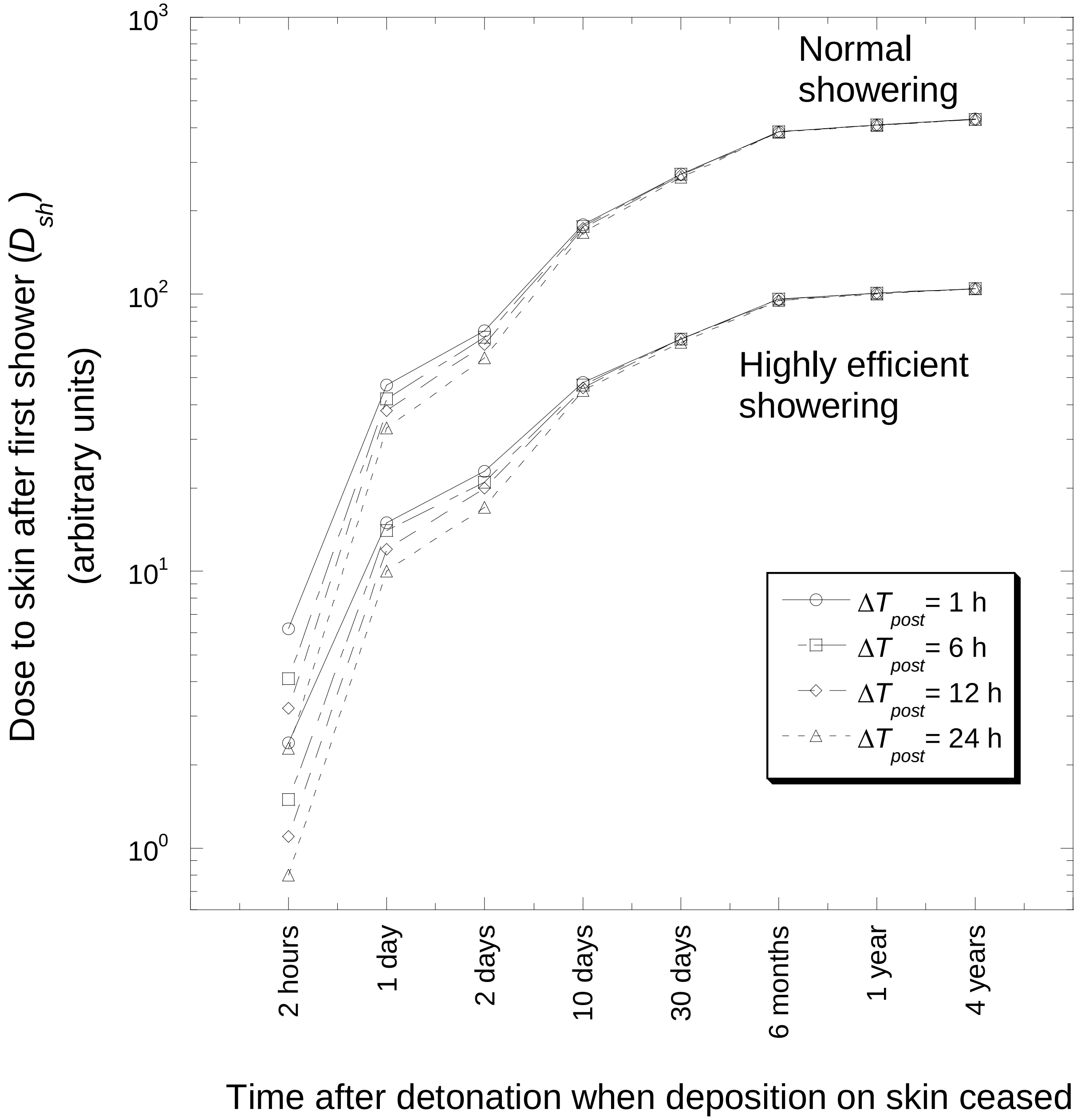

Figure 4-4. Dependence of dose to skin after first shower for normal and highly efficient showering on time after detonation when deposition on skin ceased (T_0) and time to first shower (ΔT_{post}); calculations assume deposition on trunk of body.

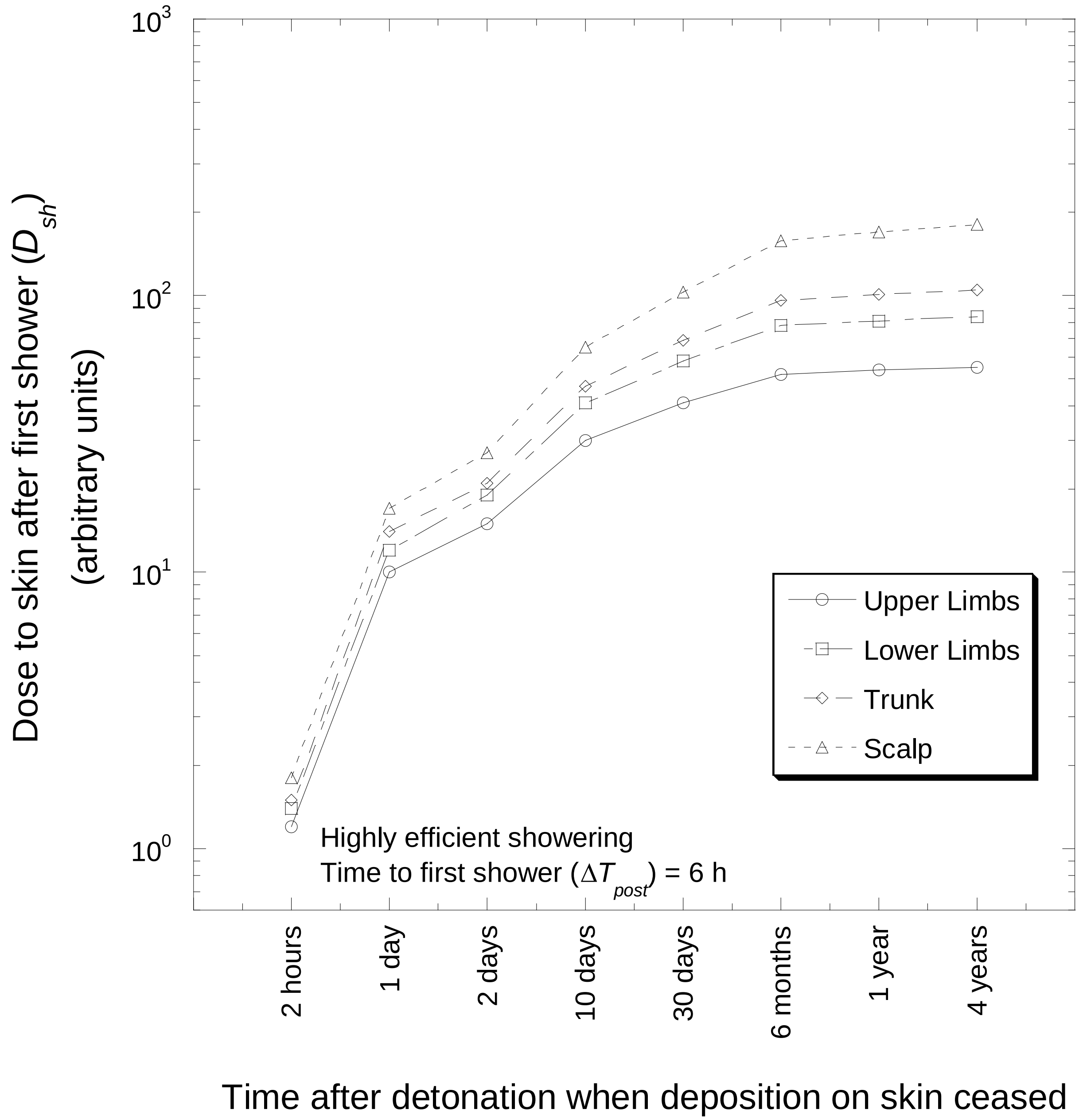

Figure 4-5. Dependence of dose to skin after first shower in different regions of body on time after detonation when deposition on skin ceased (T_0), assuming highly efficient showering and time to first shower (ΔT_{post}) of 6 hours.

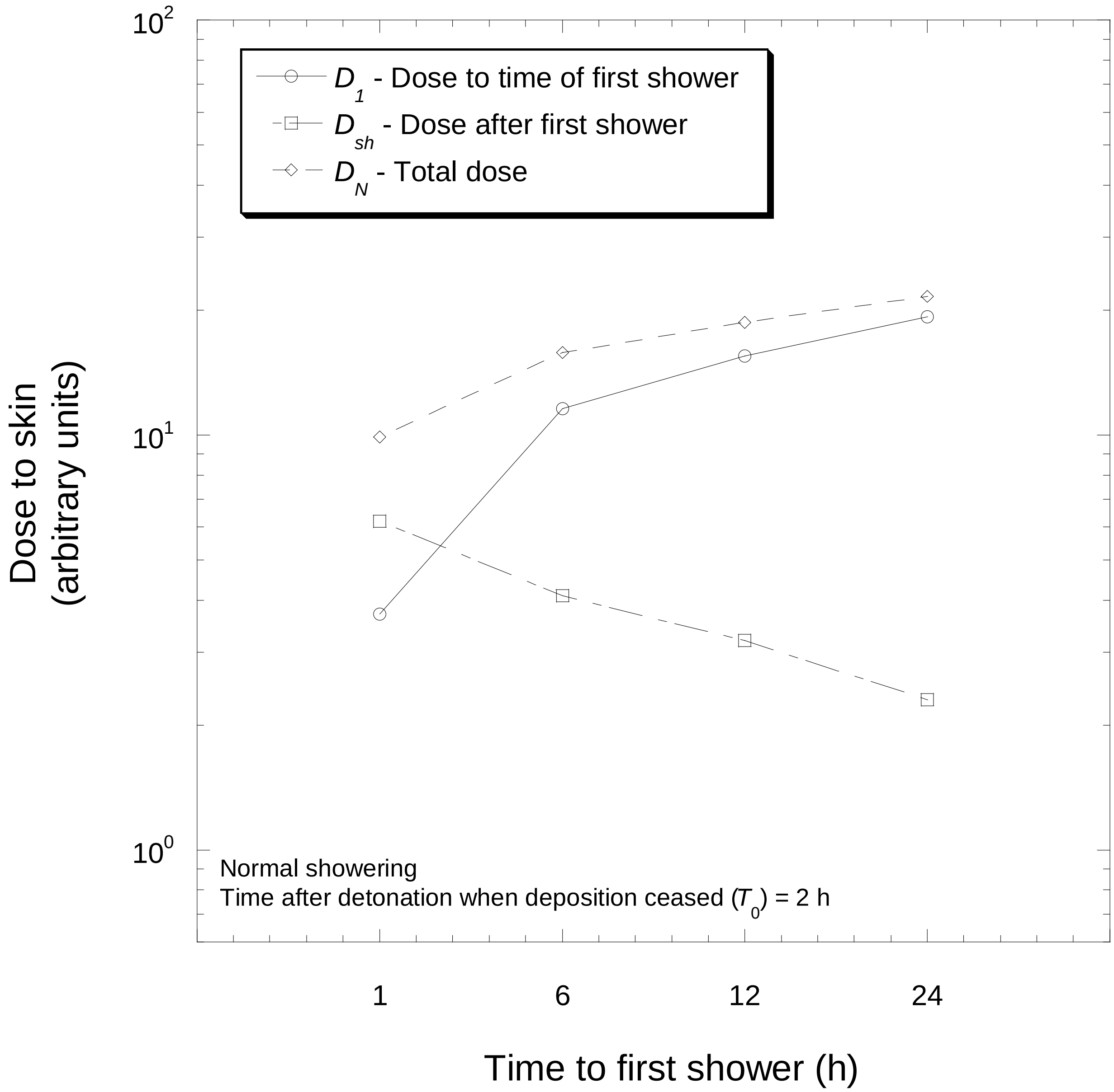

Figure 4-6. Dependence of dose to skin to time of first shower, dose to skin after first shower, and total dose on time to first shower (ΔT_{post}), assuming normal showering and time after detonation when deposition on skin ceased of 2 hours; calculations assume deposition on trunk of body.

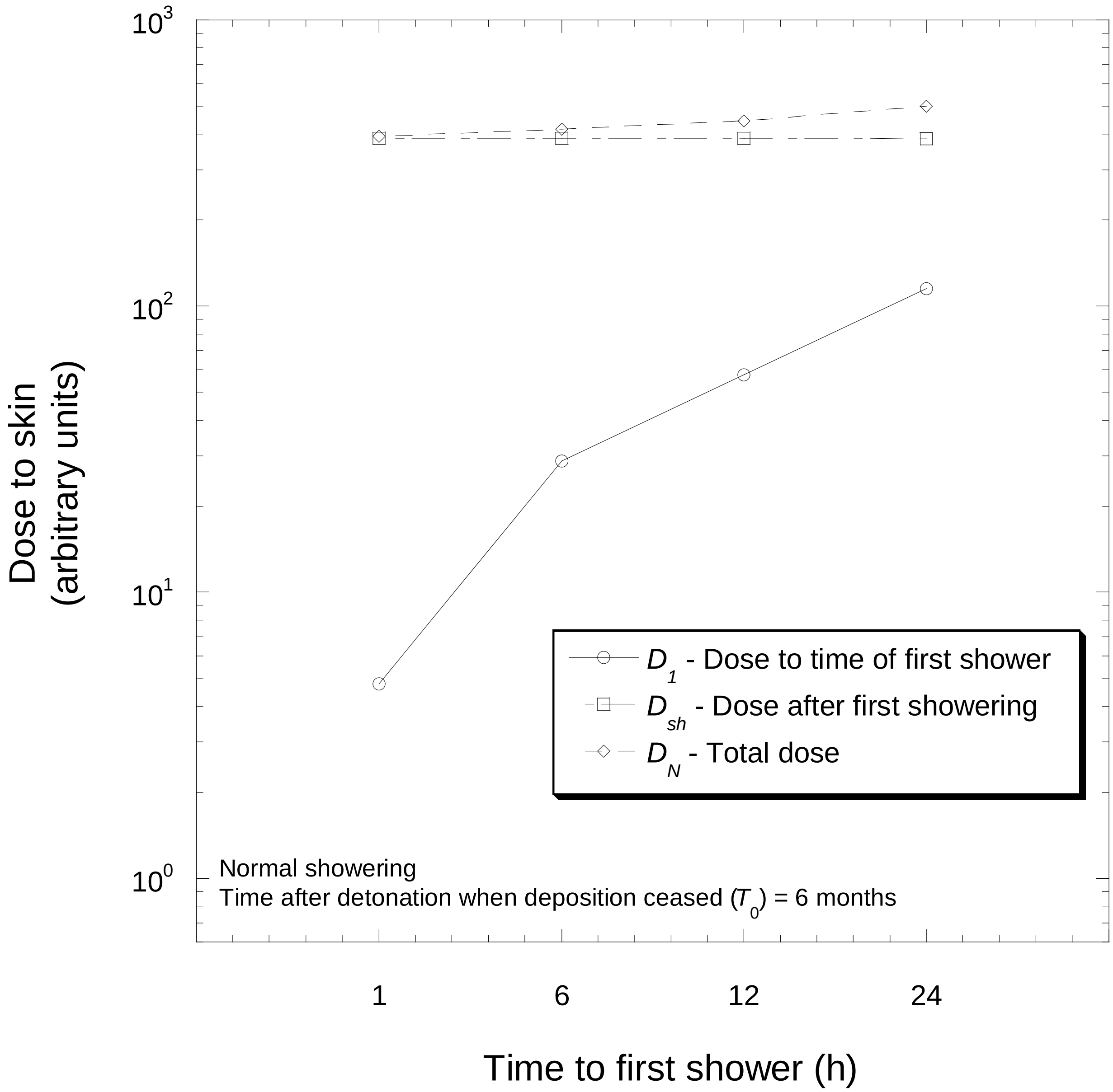

Figure 4-7. Dependence of dose to skin to time of first shower, dose to skin after first shower, and total dose on time to first shower (ΔT_{post}), assuming normal showering and time after detonation when deposition on skin ceased of 6 months; calculations assume deposition on trunk of body.

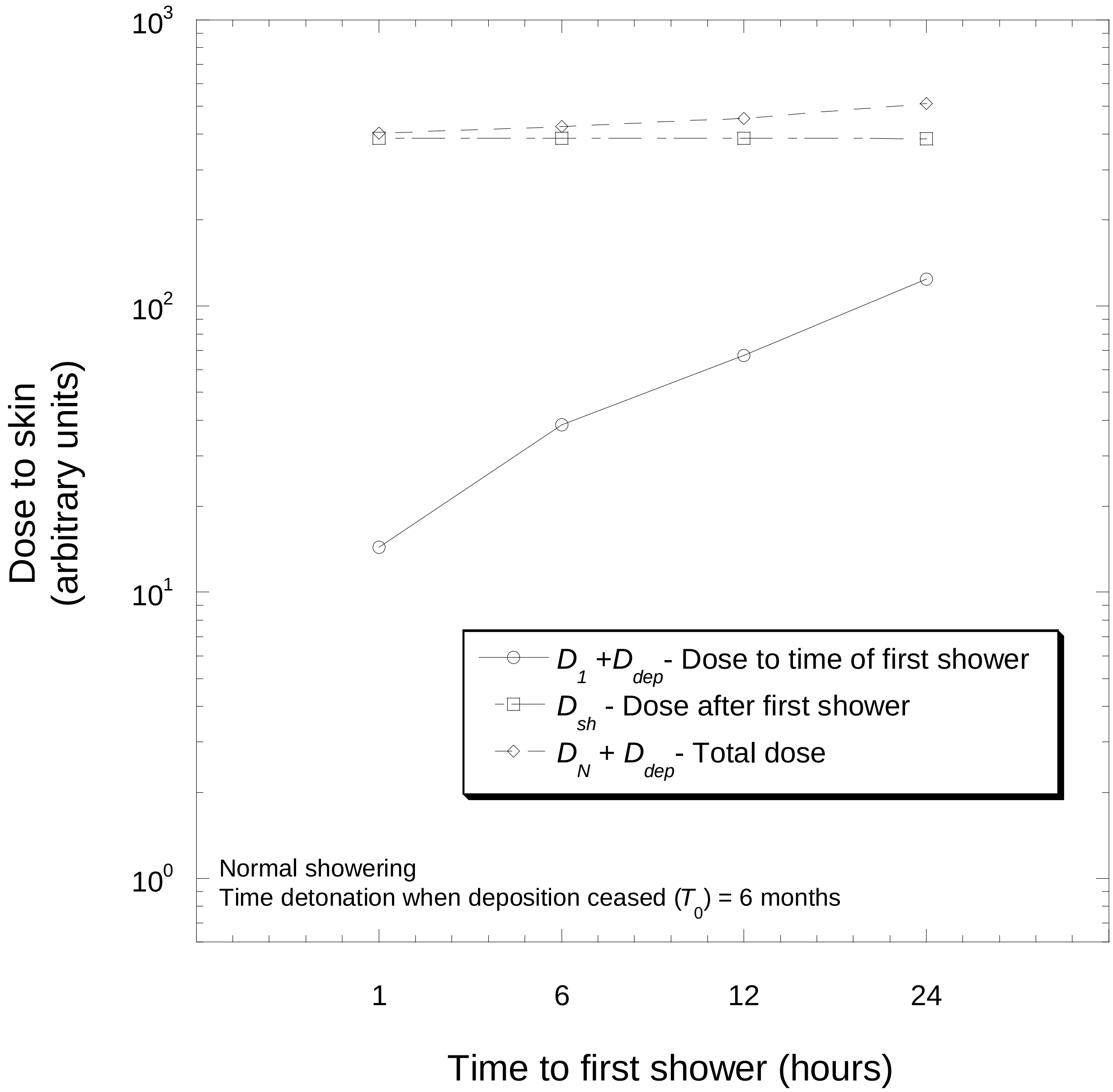

Figure 4-8. Dependence of dose to skin to time of first shower, dose to skin after first shower, and total dose on time to first shower (ΔT_{post}), assuming normal showering and time after detonation when deposition ceased of 6 months; calculations are same as in Fig. 4-7, except additional dose during continuous deposition on skin for period of 4 hours is included.

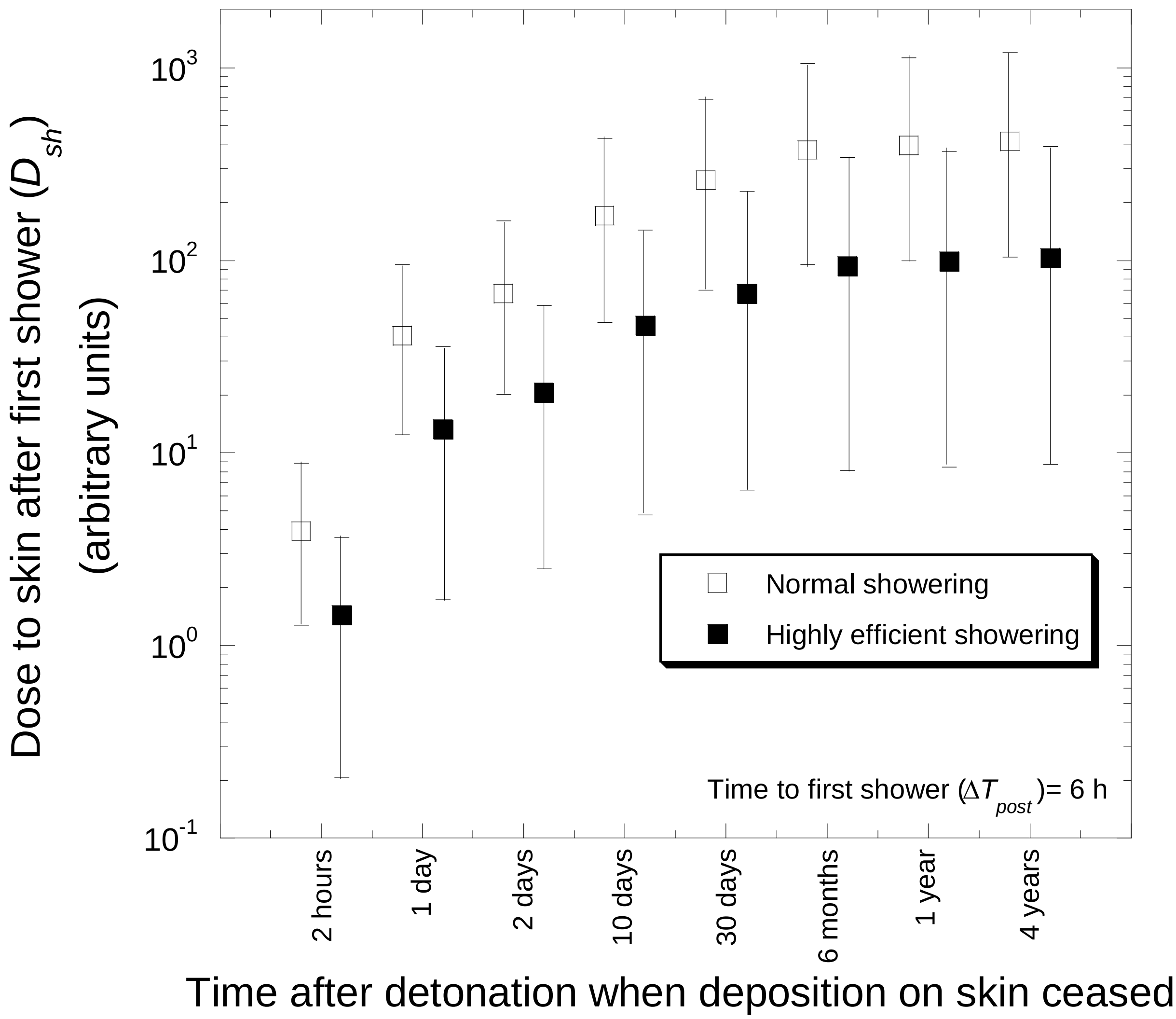

Figure 4-9. Uncertainties in doses to skin after first shower for normal and highly efficient showering and different times after a detonation when deposition on skin ceased (T_0), assuming time to first shower of 6 hours; calculations assume deposition on trunk of body.

5. DOSES TO SKIN FROM CONTAMINATED CLOTHING

In addition to direct deposition of fallout or resuspended materials onto bare skin or skin under clothing, a potentially important source of exposure of skin is radioactive material that is deposited and retained on clothing. Many radionuclides emit electrons of sufficient energy to penetrate through normal clothing and reach radiosensitive tissues in the basal layer of skin. However, on the basis of data on the thickness of clothing discussed in Section 5.3 and data on ranges of alpha particles in matter (ICRU 1993), alpha particles emitted by radioactive materials deposited on clothing are not sufficiently energetic to penetrate through clothing and the epidermis and deliver a dose to the basal layer of skin.

In cases of contamination of clothing, doses to skin can be calculated using eq. (3-1), except the activity concentration and dose-rate factor are specific to deposition on clothing:

$$\dot{D}(t) = C_{clothing}(t) \cdot DRF_{clothing} \tag{5-1}$$

where

$\dot{D}(t)$	=	dose rate to skin at time t (rem h^{-1});
$C_{clothing}(t)$	=	activity concentration of radionuclides on clothing at time t (µCi cm$^{-2}{}_{clothing}$);
$DRF_{clothing}$	=	dose-rate factor for electrons emitted by radionuclides deposited on clothing at assumed depth of radiosensitive tissues (rem h^{-1} per µCi cm$^{-2}{}_{clothing}$).

The following sections discuss available information on soil loading and deposition of airborne particles on clothing.

5.1 Soil Loading on Clothing

Black (1962) measured the accumulation of dirt on clothing, bare skin, and skin under clothing of military personnel who wore full combat fatigues and while crawling under simulated combat conditions on bare dry soil or dry grass. Accumulation of dirt on clothing was a factor of 10 to 125 higher than on skin under clothing or near clothing (on the wrist and around the neck).

Measured accumulations of soil on clothing were 13 mg cm^{-2} at the knees, 8 mg cm^{-2} at the elbows, 5 mg cm^{-2} on the back and under the belt in front, 1 mg cm^{-2} on the chest and under the belt in back, and 0.5 mg cm^{-2} at the armpits, inside of the elbow, at the side of the neck, and around the ankles. Soil loading increased if clothing was moist. The maximum soil loading on clothing that did not appear to be "caked" was 5 mg cm^{-2}.

Data summarized above suggest that a maximum credible soil loading on clothing might be about 10 mg cm^{-2}. However, the soil loading can vary greatly from one area of the body to another. In addition, soil loadings in some scenarios (e.g., digging trenches or installing equipment in the field) could be substantially less than values measured by Black (1962) under conditions of combat crawling, which involves extensive contact with the ground surface. Therefore, judgment generally would be required in selecting an appropriate soil loading.

5.2 Deposition and Retention of Airborne Particles on Clothing

Contamination of clothing by deposition and retention of airborne particles can be a significant pathway for exposure of skin. As discussed by Black (1962), Marshallese were exposed to descending fallout from Shot BRAVO at Operation CASTLE and experienced severe burns from electrons (beta particles) on areas of bare skin and areas of skin covered by clothing. Although burns in areas of bare skin were more severe than burns in areas covered by clothing, especially in folds of skin where radionuclides accumulated, it is nonetheless important to consider contamination of clothing and potential doses to skin from this exposure pathway.

In the volcanic ash studies in Costa Rica, only one contamination factor (a_h) for clothing (a value of 385 cm^2 on a blouse) was reported (Table 2-2). Since the surface area of clothing for which this a_h was measured was not indicated, an interception and retention fraction (r) cannot be estimated. Studies of military personnel who crawled through dirt or grassy areas described by Black (1962) probably are not relevant to determining deposition and retention of airborne radioactive material onto clothing.

Fogh et al. (1999) measured deposition velocities for particles of diameter 0.5, 2.5 and 8 μm on bare skin and clothing in an indoor environment. This experiment is not directly relevant to exposure to fallout from nuclear weapons testing because most fallout particles were

larger than 10 μm and deposition occurred in an outdoor environment subject to winds or other air currents. Nevertheless, data obtained by Fogh et al. (1999) indicate that deposition velocities onto clothing are smaller than deposition velocities onto bare skin. Under that condition, for a given concentration of a contaminant in air, clothing would be less contaminated than bare skin.

Deposition and retention on clothing probably depend on the texture of clothing materials and whether clothing is moist. Accumulation of fallout particles in pockets or wrinkles on clothing presumably can be significant. Deposition of small particles also could be enhanced by the presence of static electricity on clothing.

Given the lack of information on interception and retention of airborne particles on clothing, judgment is required to develop a probability distribution to represent the uncertainty in this parameter. For example, it seems unlikely that interception and retention on clothing would be higher than on bare forearms, where deposition is enhanced by the presence of hair. Thus, an average interception and retention fraction, r, for clothing probably is less than 0.06, and the maximum value on portions of clothing with no folds probably is less than 0.4 (Table 4-1). However, available data do not permit an evaluation of whether interception and retention of particles on clothing is higher or lower than interception and retention on skin of the face. In the absence of data, we assume that a reasonable representation of the uncertainty in the interception and retention fraction for clothing is the probability distribution of r for the chest specified in Table 4-1 [lognormal distribution with a GM of 0.03 and GSD of 3.9; 90% CI of (0.003, 0.28)]. This distribution is broad and includes values both higher and lower than the average interception and retention fraction for skin of the face or forearms.

Given an estimate of the interception and retention fraction, r, the effective interception and retention fraction, AR_f, can be calculated in accordance with eq. (3-4) using estimates of the particle-size adjustment factor (PS_a), enhancement due to moisture (EM), specific-activity enrichment factor (EF), and activity-weight adjustment factor (AW) obtained from Table 4-2 that apply to the assumed particle-size distribution in a given exposure scenario. Then, except for a modification of the dose-rate factor discussed in the following section, models presented in Section 3 can be used to estimate dose to skin.

5.3 Modification of Dose-Rate Factors Due to Shielding by Clothing

When radionuclides are deposited on clothing, the dose to skin is reduced compared with the dose from exposure to radionuclides on bare skin, due to the shielding provided by the layer of clothing. Estimates of doses from contamination of clothing should account for this shielding. A dose-rate factor for radionuclides on clothing can be estimated using the dose-rate factor for radionuclides on bare skin modified by a factor to account for shielding by clothing:

$$DRF_{clothing} = DRF_{skin} \cdot CMF \qquad (5\text{-}2)$$

where

$DRF_{clothing}$ = dose-rate factor for electrons emitted by radionuclides on clothing (rem h^{-1} per µCi $cm^{-2}{}_{clothing}$);

DRF_{skin} = dose-rate factor for electrons emitted by radionuclides on bare skin (rem h^{-1} per µCi $cm^{-2}{}_{skin}$);

CMF = modifying factor to account for reduction in dose rate due to shielding by layer of clothing (unitless).

The two dose-rate factors are values that apply at the same depth of radiosensitive tissues. The modifying factor *CMF* affects the dose to skin in the same way as the skin-depth modification factor (*SDMF*) introduced in Section 4.6.1 [eq. (4-4)] and discussed in Section 4.6.1.2, except *CMF* is always less than 1.0.

Barss (2000; Table 13) and Barss and Weitz (2006; Table 4) give modifying factors to represent the shielding provided by light clothing that apply to exposure to mixtures of radionuclides in fallout on the ground surface. The depth of radiosensitive tissues was assumed to be 7 mg cm^{-2}, and light clothing was assumed to be 0.7 mm thick with a density of 0.4 g cm^{-3}, which is equivalent to a thickness of tissue of 28 mg cm^{-2} (Barss 2000). Modifying factors for light clothing were calculated as a function of height above ground and time after a detonation. Modifying factors at a height of 1 cm are the best approximation of modifying factors that apply to contamination on clothing. The modifying factor for light clothing at a height of 1 cm ranges from 0.4 to 0.6, depending on time after detonation. Higher values occur at times within one day, and lower values occur at times of one week or later.

For a 0.7-mm layer of clothing with an equivalent thickness of tissue of 28 mg cm^{-2}, the total depth of radiosensitive tissues at an average depth of 7 mg cm^{-2} below the body surface is 35 mg cm^{-2}. Thus, in regions of the body other than the palms of the hands or soles of the feet, the modifying factor for clothing (*CMF*) should be similar to the skin-depth modification factor (*SDMF*) in eq. (4-4) that applies at a nominal depth of 40 mg cm^{-2} when radionuclides are deposited on bare skin. This *SDMF*, which is discussed in Section 4.6.1.2.3, is represented by a triangular probability distribution with a minimum at 0.1, mode at 0.3, and maximum at 0.6 (Table 4-2). The assumed probability distribution encompasses the modifying factors reported by Barss (2000) and Barss and Weitz (2006) that apply at 1 cm above ground, which range from 0.4 to 0.6. The assumed range of *CMF* is sufficiently broad that it should be applicable in regions of the body where the nominal depth of radiosensitive tissues is 4 mg cm^{-2} (face, forehead, neck, shoulders, torso, and upper legs) or 8 mg cm^{-2} (arms or lower legs).

6. EVALUATION OF IMPORTANCE OF DOSES TO SKIN FROM DERMAL CONTAMINATION

External exposure of skin to beta-emitting radionuclides on the ground surface is an important exposure pathway for many military participants. Thus, one way to evaluate the potential importance of doses to skin from dermal contamination is to compare them with doses from exposure to beta emitters on the ground surface. In this section, we investigate conditions under which the dose to skin from dermal contamination could be at least a substantial fraction of the dose from beta emitters on the ground. The general approach is to estimate ratios of doses from dermal contamination to doses from ground-surface exposure in defined scenarios.

In this assessment, comparisons of electron doses to skin from dermal contamination and exposure to a contaminated ground surface in different scenarios are based on estimated inventories of radionuclides in fallout at 2 days and 4 years after a nuclear detonation involving fission of ^{235}U. A total of 82 radionuclides were taken into account in dose estimates at 2 days and 27 in dose estimates at 4 years (Trabalka and Kocher 2007).

The dose rate to skin from a single beta emitter that is assumed to be uniformly deposited on the ground surface is calculated as:

$$\dot{D}_{gs} = C_{gs} \cdot DRF_{gs} \tag{6-1}$$

where

DRF_{gs} = dose-rate factor at height of 1 m above ground for radionuclide on the ground surface (rem h^{-1} per μCi $cm^{-2}{}_{ground}$)

C_{gs} = activity concentration of radionuclide on the ground surface (μCi $cm^{-2}{}_{ground}$ per fission).

The dose rate from all radionuclides in fallout combined is calculated on the basis of an estimated activity concentration of each radionuclide on the ground surface per fission of ^{235}U.[27] The activity of each radionuclide per fission was obtained by multiplying its fission yield

[27] Only relative activities of radionuclides are important in evaluating the relative importance of doses from dermal contamination and ground-surface exposure.

(number of atoms per fission) given by England and Rider (1994) by its activity per atom adjusted by a factor to account for decay and buildup of any radioactive decay products at 2 days and 4 years after detonation. Trabalka and Kocher (2007) summarize the assumed activities of radionuclides per fission at 2 days and 4 years after detonation. Dose-rate factors for exposure to beta emitters on the ground surface were obtained from Eckerman and Ryman (1993).

Equation (6-1) is integrated over the duration of exposure to a contaminated ground surface (ΔT_{ground}) to obtain doses to skin per fission. The duration of exposure to radionuclides on the ground surface can be different from the duration of exposure to radionuclides deposited on skin. For example, an exposed individual can leave an area where the ground surface is contaminated, but contamination of skin will continue for an additional period of time, until the next shower.

Doses to skin from dermal contamination are estimated for each radionuclide using equations presented in Sections 3.2 and 3.3 for descending fallout and resuspension of material from the ground surface, respectively. Total doses are obtained by summing the dose from each radionuclide. Calculated doses to skin do not account for effects of fractionation or differences in radionuclide inventories depending on the fission mode (e.g., fission of ^{238}U or ^{239}Pu compared with the assumed fission of ^{235}U). However, the importance of dermal contamination should not be significantly affected by assumptions regarding fractionation or fission mode.

Scenarios of dermal contamination that were compared with ground-surface exposure in this analysis include exposure due to (1) descending fallout, (2) resuspension by vehicular traffic, (3) wind-driven resuspension, and (4) resuspension of old fallout by the thermal pulse or blast wave produced in a nuclear detonation. In all resuspension scenarios, exposure was assumed to occur at 2 days or 4 years after a detonation. The only parameters in the calculations that differ at the two times are the resuspension factor for wind-driven resuspension and the relative activities of different radionuclides. In each scenario, we estimated doses to skin of the face and arms, which are regions of body where deposition of airborne particles on bare skin most likely occurs. Doses to the arms generally are higher than doses to the face, due to the greater retention of depositing material on hairy portions of the forearms.

None of the calculations for the different scenarios discussed in this section take into account the effect of inefficient showering in increasing doses from dermal contamination; i.e.,

all contamination on skin is assumed to be removed at the time of the first shower after deposition on skin occurred. Neglect of inefficient showering results in underestimates of the importance of doses from dermal contamination relative to doses from exposure to electrons emitted by radionuclides on the ground surface. The importance of inefficient showering is illustrated by calculations presented in Section 4.7.3 and Appendix E.

Two scenarios for exposure to descending fallout were considered. In both scenarios, contamination of skin was modeled as an acute event, as described in Section 3.2. In one scenario, we assumed that, due to the proximity to ground zero, exposure to descending fallout at NTS involved an unknown mixture of large and small particles.[28] We also assumed that exposure to fallout deposited on the ground surface occurred over a period of 4 hours, and that an individual showered at 12 hours after deposition on skin occurred. In the second scenario, we assumed that exposure occurred far from ground zero in the Pacific and, thus, that exposure to descending fallout involved small particles only. We also assumed that exposure to fallout deposited on the ground surface occurred over a period of 8 hours, and that an individual showered at 12 hours after deposition on skin occurred.

A single scenario involving resuspension of radioactive material by vehicular traffic at NTS and exposure while marching behind vehicles was analyzed. We assumed that dust generated by vehicles at the height of the face or arms contained only small particles. We also assumed that exposure in a contaminated area occurred over a period of 4 hours, and that showering occurred at 8 hours after leaving that area.

Exposure to radioactive material resuspended by winds at NTS or in the Pacific was considered. This type of scenario involves exposure to small particles under normal conditions. We assumed that the duration of outdoor activities in a contaminated area was 8 hours, and that showering occurred at 4 hours after leaving that area.

Two scenarios of exposure to old fallout that was resuspended by a nuclear detonation at NTS were considered. The first scenario involved exposure of forward observers who were located in the blast-wave region near ground zero at the time of a detonation. Dermal

[28] Such a distribution of particle sizes could occur close to ground zero if, for example, exposure to descending fallout occurred at locations away from the centerline of the fallout plume, where the fraction of the activity of radionuclides that was carried by smaller particles should be larger.

contamination was assumed to be due to the combined effects of the initial shower of large resuspended fallout particles, which occurred essentially at the time of detonation, and deposition of smaller resuspended particles, which occurred during the remainder of the time that forward observers spent in the blast-wave region. The second scenario involved exposure of maneuver troops who entered the thermal-pulse or blast-wave region some tens of minutes after detonation (i.e., after large resuspended particles had redeposited on the ground) and were exposed to small particles in the lingering dust cloud; separate results are presented for exposure of maneuver troops in the two regions. We assumed that forward observers and maneuver troops spent 2 hours in a contaminated area, and that showering occurred at 12 and 10 hours after deposition onto skin ceased, respectively.

In all scenarios described above, values of model parameters were chosen to represent the specified conditions of exposure. For example, the average wind speed was assumed to be 4 m s^{-1} at NTS and 5 m s^{-1} in the Pacific; this difference results in higher doses due to resuspension by winds in the Pacific. Values of the particle-size adjustment factor (PS_a), specific-activity enrichment factor (*EF*), and activity-weight adjustment factor (*AW*) were chosen on the basis of the assumed particle sizes of resuspended material (large, small, or unknown mixture), and values of the adjustment factor to account for moisture on skin (*EM*) were chosen to represent conditions at NTS or in the Pacific. Point estimates of dose were obtained by performing calculations using the deterministic values of parameters in Tables 4-1, 4-2 and 4-3. All parameter values are summarized by exposure scenario in Appendix C, Tables C-1 to C-6.

A comparison of doses to skin from dermal contamination with doses from exposure to a contaminated ground surface is presented in Table 6-1 for exposures that took place shortly after a detonation and in Table 6-2 for exposures that took place years after a detonation. These comparisons indicate that the dose from dermal contamination could be at least a significant fraction of the dose from ground-surface exposure in the following scenarios:

1. Exposure to descending fallout at NTS or in the Pacific;
2. Exposure to fallout that was resuspended by vehicular traffic at any time after a detonation at NTS (this scenario was not analyzed in the Pacific);
3. Exposure to material that was resuspended by winds at times shortly after a detonation at NTS or in the Pacific;

4. Exposure of maneuver troops at NTS who entered the thermal-pulse region at some time (e.g., tens of minutes) after a detonation, without regard for the age of previously deposited fallout.

The importance of doses from dermal contamination relative to doses from ground-surface exposure in these scenarios would increase substantially if the effect of inefficient showering were taken into account, as illustrated in Section 4.7.3.

Doses from dermal contamination are unimportant in the calculations for the other exposure scenarios considered in this evaluation. In resuspension scenarios, doses from dermal contamination are unimportant compared with doses from ground-surface exposure when the fraction of the activity of radionuclides on the ground that is resuspended is very small. Exposure to large particles only also results in low doses from dermal contamination relative to doses from ground-surface exposure because large particles are not easily retained on skin and the activity-weight adjustment factor (*AW*) is low.

In scenarios involving wind-driven resuspension, the duration of exposure was assumed to be 8 hours, followed by a period of 4 hours until an exposed individual was assumed to remove contamination from skin by showering. In the Pacific, however, exposure often occurred over a period of weeks or months. In such cases, doses between successive daily showers would need to be summed to obtain a total dose.

Results in Tables 6-1 and 6-2 were obtained using deterministic estimates of parameter values and, therefore, are based on nominal point estimates of dose to the skin for each pathway. An uncertainty analysis was not performed in this comparison exercise. However, we believe that such an analysis would show that the dose to skin from dermal contamination could increase greatly in importance relative to the dose from ground-surface exposure in many scenarios when upper credibility limits (95^{th} percentiles) of estimated doses are compared. For example, in some resuspension scenarios, the 95^{th} percentile of the resuspension factor is two orders of magnitude higher than the median estimate (Table 4-3). Since this uncertainty is much larger than the uncertainty in estimating the dose from ground-surface exposure, the dose from dermal contamination relative to the dose from ground-surface exposure at the 95^{th} percentile would be at least a factor of 100 higher.

In summary, calculations presented in this section indicate that, in some types of exposure scenarios, electron doses to skin from dermal contamination are significant, and sometimes dominant, compared with electron doses to skin from exposure to radionuclides on the ground surface. Since electrons doses to skin from radionuclides on the ground are much higher than doses from photons (Barss 2000), we can conclude that electron doses to skin from dermal contamination can be an important contributor to the total dose to skin from all exposure pathways. Results of our comparative analysis and judgments about an upper credibility limit of these doses indicate that electron doses to skin from dermal contamination should be estimated in most exposure scenarios.

Table 6-1. Estimated doses to skin from external exposure to beta-emitting radionuclides on ground surface and doses to skin from dermal contamination in selected scenarios for exposure to airborne particles – Exposure at times shortly after a detonation[a]

Exposure scenario	Dose from ground-surface exposure[b] (rem per fission)	Dose from dermal contamination (rem per fission)	Ratio of doses (dermal/ground)
Descending fallout			
NTS, near ground zero			
Face	6.1×10^{-11}	9.5×10^{-12}	0.16
Arms	6.1×10^{-11}	2.6×10^{-11}	0.43
Pacific, far from ground zero			
Face	1.1×10^{-10}	1.2×10^{-10}	1.1
Arms	1.1×10^{-10}	3.4×10^{-10}	3.1
Resuspension by vehicular traffic (marching behind vehicles)			
NTS, near ground zero			
Face	6.1×10^{-11}	1.9×10^{-11}	0.31
Arms	6.1×10^{-11}	5.2×10^{-11}	0.85
Resuspension by winds			
NTS, near ground zero			
Face	1.1×10^{-10}	5.9×10^{-12}	0.054
Arms	1.1×10^{-10}	1.6×10^{-11}	0.15
Pacific, far from ground zero			
Face	1.1×10^{-10}	1.1×10^{-11}	0.10
Arms	1.1×10^{-10}	3.1×10^{-11}	0.29
Resuspension by nuclear detonation at NTS – forward observers			
Face	3.3×10^{-11}	5.3×10^{-14}	0.0016
Arms	3.3×10^{-11}	1.5×10^{-13}	0.0045
Resuspension by nuclear detonation at NTS – maneuver troops in blast-wave region			
Face	3.3×10^{-11}	5.2×10^{-14}	0.0016
Arms	3.3×10^{-11}	1.4×10^{-13}	0.0044
Resuspension by nuclear detonation at NTS – maneuver troops in thermal-pulse region			
Face	3.3×10^{-11}	5.2×10^{-12}	0.16
Arms	3.3×10^{-11}	1.4×10^{-11}	0.44

[a] Exposure is assumed to occur at 2 days after a detonation.

[b] Doses from exposure to radionuclides on ground surface are scenario-dependent, due to differences in assumed duration of exposure.

Table 6-2. Estimated doses to skin from external exposure to beta–emitting radionuclides on ground surface and doses to skin from dermal contamination in selected scenarios for exposure to airborne particles – Exposure at long times after a detonation[a]

Exposure scenario	Dose from ground-surface exposure[b] (rem per fission)	Dose from dermal contamination (rem per fission)	Ratio of doses (dermal/ground)
Resuspension by vehicular traffic (marching behind vehicles)			
NTS, near ground zero			
Face	6.7×10^{-15}	2.2×10^{-15}	0.32
Arms	6.7×10^{-15}	6.0×10^{-15}	0.90
Resuspension by winds			
NTS, near ground zero			
Face	1.2×10^{-14}	2.1×10^{-17}	0.0017
Arms	1.2×10^{-14}	5.8×10^{-17}	0.0047
Pacific, far from ground zero			
Face	1.2×10^{-14}	4.0×10^{-17}	0.0032
Arms	1.2×10^{-14}	1.1×10^{-16}	0.0089
Resuspension by nuclear detonation at NTS – forward observers			
Face	3.8×10^{-15}	6.1×10^{-18}	0.0016
Arms	3.8×10^{-15}	1.7×10^{-17}	0.0045
Resuspension by nuclear detonation at NTS – maneuver troops in blast-wave region			
Face	3.8×10^{-15}	6.0×10^{-18}	0.0016
Arms	3.8×10^{-15}	1.7×10^{-17}	0.0044
Resuspension by nuclear detonation at NTS – maneuver troops in thermal-pulse region			
Face	3.8×10^{-15}	6.0×10^{-16}	0.16
Arms	3.8×10^{-15}	1.7×10^{-15}	0.44

[a] Exposure is assumed to occur at 4 years after a detonation.

[b] Doses from exposure to radionuclides on ground surface are scenario-dependent, due to differences in assumed duration of exposure.

7. SUMMARY AND CONCLUSIONS

Many military personnel who participated in the atmospheric nuclear-weapons testing program were subjected to contamination of skin and clothing by radioactive particles, and such contamination could have been an important contributor to external doses to skin. The primary purpose of this report is to present an approach to estimating doses to radiosensitive tissues in the basal layer of skin from dermal contamination by deposition of particles in descending fallout from a nuclear weapons detonation or deposition of radioactive material that was resuspended from the ground surface or other surfaces (e.g., weather deck of a ship) by various human activities or the wind. This report also considers doses to skin when clothing is contaminated or when dermal contamination occurs as a result of direct contact with a contaminated ground surface or object. The main concern of this report is estimation of doses to skin from exposure to electrons (beta particles) emitted by radionuclides on the body surface. Estimation of doses from dermal contamination by radionuclides that emit alpha particles also is considered. Deposition of descending fallout or resuspended radioactive material is expected to produce uniform contamination on relatively large areas of the body surface. However, levels of contamination of skin are expected to vary in different regions of the body. Doses to skin from exposure to individual "hot" particles are not treated in this report.

This report makes four contributions to the development of a methodology to estimate doses to skin from dermal contamination. The first is a summarization of relevant experimental data on dermal contamination, including data on soil loadings on skin in different regions of the body under various conditions, data on deposition and retention of volcanic ash particles on skin under field conditions, and data obtained in wind-tunnel studies and in indoor environments. The second contribution is the development of models to estimate contamination of skin by deposition of descending or resuspended fallout or by contact with contaminated ground or other surfaces. Once activity concentrations of radionuclides on skin are estimated for an exposure scenario of interest, doses to skin are estimated using published dose-rate factors (dose rates to skin per unit activity concentration) for beta-emitting radionuclides or dose-rate factors for alpha-emitting radionuclides that we calculated on the basis of a published model for alpha dosimetry in the basal layer of skin. The third contribution is the development of models to take into account the effect of incomplete removal of radionuclides from skin by showering in

increasing doses from dermal contamination. On the basis of available data on efficiencies of removal of contamination from skin by washing and turnover times of skin cells by exfoliation, these models represent the fraction of contamination remaining on skin after the first shower following a deposition and after subsequent daily showers. The fourth contribution is the development of probability distributions to represent uncertainties in parameters in models to estimate activity concentrations of radionuclides that are deposited and retained on skin in various scenarios, uncertainties in parameters in models to estimate the effect of inefficient showering, and uncertainties in dose-rate factors for beta-emitting radionuclides.

Modeling of skin contamination by direct contact with contaminated soil or other materials relies on relevant data on soil loading on skin and clothing. Any calculated or assumed dermal soil loading in scenarios involving contact transfer of contaminated material should not exceed 2 mg_{soil} per cm^2_{skin} and in most cases should be less than 1 mg_{soil} per cm^2_{skin}. Soil loading on clothing can be as high as 13 mg cm^{-2}, but loadings higher than 5 mg cm^{-2} appear as "caked" soil and are less likely to occur and to remain on clothing for long periods after accumulation.

Modeling of skin contamination by deposition of descending fallout is based on estimates of the fraction of incident material that is intercepted and retained in various regions of the body. Interception and retention fractions are derived mainly on the basis of measured accumulations of ash particles on the ground surface and in different regions of the body of human subjects while engaged in outdoor activities following eruption of the Irazu Volcano in Costa Rica.

On the basis of data obtained in the volcanic ash studies, we would expect that skin of the face, shoulders, and back of the torso should intercept and retain, on average, about 1.5% of the mass of airborne particles that impact those regions of the body. We also would expect that an average interception and retention fraction should be about 6% on the forearms and upper legs, 3% on the chest, and 17% on the scalp; these higher values probably are largely a consequence of enhanced retention due to the presence of hair in those regions. Interception and retention fractions greater than 1.0 are possible in special regions of the body, such as the back of the neck under a collar, behind the ears, or under a belt, where material deposited on other parts of the body can migrate and accumulate.

Interception and retention fractions derived from the volcanic ash studies are adjusted when applied to exposure conditions for military personnel that were different from those in

Costa Rica. Particle size is an important determinant of retention on skin. Studies indicate that retention on skin decreases with increasing particle size for particle diameters greater than about 50 μm, whereas particles of diameter less than about 50 μm have similar retention on skin. On the basis of this information, interception and retention fractions are adjusted to account for a difference between particle-size distributions of airborne materials to which military personnel were exposed in various scenarios at NTS or in the Pacific and particle-size distributions in the volcanic ash studies. In addition, since retention is enhanced when moisture is present on skin, interception and retention fractions obtained from the volcanic ash studies are adjusted downwards (or upwards) when exposure occurred under conditions where there was less (or more) humidity than in Costa Rica.

Interception and retention fractions obtained in the volcanic ash studies and the adjustments to account for differences in particle-size distributions and the effect of moisture on skin that are used in applying those fractions to exposures of military personnel are defined with respect to the mass of airborne particles. Estimation of activity concentrations of radionuclides on skin, which is the quantity of interest in estimating dose, takes into account two other possible effects related to particle-size distributions in descending or resuspended fallout. First, since skin preferentially retains small particles, the specific activity of material retained on skin is enhanced compared with the specific activity of material incident on the body when radionuclides are preferentially distributed on the surface of particles. This adjustment is largest when airborne material consists mainly of large particles. Second, measurements at NTS showed that large particles in weapons fallout carried most of the activity at locations within a few miles of ground zero. Consequently, since small particles are preferentially retained on skin, the activity concentration of fallout deposited on skin can be much lower than the activity concentration on the ground surface when most fallout particles are large. This effect is taken into account using an adjustment factor that represents the difference between activity and weight particle-size distributions in fallout.

To estimate contamination of skin due to deposition of resuspended fallout, an activity concentration of radionuclides in air relative to the activity concentration on the ground or other surface is first estimated using a resuspension factor. A flux density of resuspended material incident on the body (activity per unit area per unit time) is calculated using a wind speed or

deposition velocity. Interception and retention fractions for descending fallout then are used to estimate the fraction of the activity of resuspended material incident on the body that is deposited and retained on skin. Contamination of skin due to deposition of resuspended material of a given particle size increases with increasing wind speed or deposition velocity.

In cases of exposure to descending fallout, deposition on skin occurs during a relatively short time and can be modeled as an acute event. In contrast, dermal contamination by resuspension of nuclear weapon debris usually can be modeled as a continuous process, especially when deposition of resuspended fallout onto skin can take place over many hours or days (e.g., in cases of wind-driven resuspension on residence islands in the Pacific).[29]

Models to represent the effect of inefficient showering developed in this report indicate that this effect can be important in estimating doses to skin in many cases, even when showering is assumed to be more efficient in removing radioactive contamination from skin than normal showering. The importance of the dose received after the time of the first shower relative to the dose received before the first shower increases as the time after a detonation when exposure to descending or resuspended fallout occurred increases, due to reductions in the rate of decrease of the activity of all radionuclides in fallout combined with increasing time after a detonation, and increases as the time between deposition on skin and the first shower decreases. At times shortly after a detonation, when doses from dermal contamination could be relatively high, calculations indicate that inefficient showering may increase doses to skin by less than a factor of two, whereas at times long after a detonation, when doses from dermal contamination would be relatively low, the increase in doses due to inefficient showering could be much higher (e.g., about an order of magnitude, depending on the time between deposition and the first shower).

Doses to skin from exposure to the beta-emitting radionuclides on the body surface are estimated using published dose-rate factors for specific radionuclides that apply at a depth below the body surface of 7 mg cm^{-2}. Those dose-rate factors are applied to mixtures of radionuclides in fallout and are adjusted to account for different thicknesses of the epidermis in various regions

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[29] Dermal contamination by deposition of resuspended material can be modeled as an acute event in cases of exposure of forward observers at NTS to large particles in fallout that was resuspended by the blast wave produced in a nuclear detonation, when material is immediately lofted into the air and large particles, which carried most of the activity, fell rapidly to Earth (see Section 3.3.4). Prolonged exposures of forward observers to smaller resuspended particles that may have remained airborne for times on the order of hours can be modeled by assuming continuous deposition.

of the body. Other effects that are taken into account in estimating dose-rate factors include reductions in doses from electrons due to shielding provided by particles to which radionuclides are attached or by clothing on which radionuclides are deposited and reductions in doses due to neglect of backscattering in air in the published dose-rate factors.

Dose-rate factors for important alpha-emitting radionuclides in fallout were calculated in this report on the basis of a published dosimetry model. Although dose-rate factors for alpha emitters usually are much higher than dose-rate factors for beta emitters when alpha particles are sufficiently energetic to irradiate cells in the basal layer, alpha doses to skin of military personnel are not expected to be important relative to doses from electrons when it is considered that activities of alpha emitters in fallout are much lower than the total activity of all beta emitters.

This report presents example calculations of doses to skin from exposure to electrons emitted by radionuclides on the body surface in specific exposure scenarios at NTS and in the Pacific. Results of these calculations indicate that, for exposure to descending fallout or resuspended material, electron doses to skin from dermal contamination can be a significant and sometimes dominant contributor to the total dose to skin from all exposure pathways.

As in all dose reconstructions, estimation of doses to skin from dermal contamination requires significant judgment by an analyst. While the modeling approaches are straightforward, the necessary parameters are not well known. Probability distributions and point estimates of parameters for a number of exposure situations believed to be important (and common) are recommended in this report. Different assumptions about parameter values may be needed for other exposure situations.

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APPENDIX A

ADDITIONAL DATA USED IN ESTIMATING DOSES TO SKIN FROM DERMAL CONTAMINATION

A.1 Data on Soil Loading on Skin and Clothing

This section summarizes data obtained in studies of accumulation and retention of soil particles on skin during various activities. These data provide estimates of the mass of soil retained per unit area of skin that can be used in estimating dermal contamination by processes other than deposition of descending or resuspended fallout (Section 3.4). An estimate of the specific activity of contaminated soil (μCi mg^{-1}_{soil}) then can be used to estimate an activity concentration on skin (μCi cm^{-2}_{skin}).

Various studies in which accumulation of soil on skin of human subjects was estimated are summarized in Table A-1. Measurements of soil loading on skin (mg_{soil} cm^{-2}_{skin}) obtained from those studies are given in Table A-2.

Estimates of average soil loadings on skin and clothing of military personnel who performed combat crawling through areas with bare soil and dry clipped grass are provided in Table A-3, and information on the variability of measured soil loadings in the same study are provided in Tables A-4 and A-5.

Table A-1. Summary of studies to estimate soil loading on skin resulting from various activities (EPA 1997)

Activity	Month	Duration (h)	N[a]	Males	Females	Age	Conditions	Clothing
Indoor								
Tae Kwon Do	Feb.	1.5	7	6	1	8–42	Carpeted floor	All in long sleeve-long pans martial arts uniform, sleeves rolled back, barefoot
Greenhouse Workers	Mar.	5.25	2	1	1	37–39	Plant watering, spraying, soil blending, sterilization	Long pants, elbow length short sleeve shirt, no gloves
Indoor Kids No. 1	Jan.	2	4	3	1	6–13	Playing on carpeted floor	3 of 4 short pants, 2 of 4 short sleeves, socks, no shoes
Indoor Kids No. 2	Feb.	2	6	4	2	3–13	Playing on carpeted floor	5 of 6 long pants, 5 of 6 long sleeves, socks, no shoes
Outdoor								
Daycare Kids No. 1a	Aug.	3.5	6	5	1	1–6.5	Indoors: linoleum surface; outdoors: grass, bare earth, barked area	4 of 6 in long pants, 4 of 6 short sleeves, shoes
Day Daycare Kids No. 1b	Aug.	4	6	5	1	1–6.5	Indoors: linoleum surface; outdoors: grass, bare earth, barked area	4 of 6 in long pants, 4 of 6 short sleeves, no shoes
Daycare Kids No. 2c	Sept.	8	5	4	1	1–4	Indoors, low napped carpeting, linoleum surfaces	4 of 5 long pants, 3 of 5 long sleeves, all barefoot for part of the day
Daycare Kids No. 3	Nov.	8	4	3	1	1–4.5	Indoors: linoleum surface, outside: grass, bare earth, barked area	All long pants, 3 of 4 long sleeves, socks and shoes
Soccer No. 1	Nov.	0.67	8	8	0	13–15	Half grass-half bare earth	6 of 8 long sleeves, 4 of 8 long pants, 3 of 4 short pants and shin guards
Soccer No. 2	Mar.	1.5	8	0	8	24–34	All-weather field (sand-ground tires)	All in short sleeve shirts, shorts, knee socks, shin guards
Soccer No. 3	Nov.	1.5	7	0	7	24–34	All-weather field (sand-ground tires)	All in short sleeve shirts, shorts, knee socks, shin guards
Groundskeepers No. 1	Mar.	1.5	2	1	1	29–52	Campus grounds, urban horticulture center, arboretum	All in long pants, intermittent use of gloves
Groundskeepers No. 2	Mar.	4.25	5	3	2	22–37	Campus grounds, urban horticulture center, arboretum	All in long pants, intermittent use of gloves
Groundskeepers No. 3	Mar.	8	7	5	2	30–62	Campus grounds, urban horticulture center, arboretum	All in long pants, intermittent use of gloves
Groundskeepers No. 4	Aug.	4.25	7	4	3	22–38	Campus grounds, urban horticulture center, arboretum	5 of 7 in short sleeve shirts, intermittent use of gloves
Groundskeepers No. 5	Aug.	8	8	6	2	19–64	Campus grounds, urban horticulture center, arboretum	5 of 8 in short sleeve shirts, intermittent use of gloves
Landscape/Rockery	June	9	4	3	1	27–43	Digging (manual and mechanical), rock moving	All long pants, 2 long sleeves, all socks and boots
Irrigation Installers	Oct.	3	6	6	0	23-41	Landscaping, surface restoration	All in long pants, 3 of 6 short sleeve or sleeveless shirts

Table is continued on following page.

Table A-1. Summary of studies to estimate soil loading on skin resulting from various activities (EPA 1997) (continued)

Activity	Month	Duration (h)	N[a]	Males	Females	Age	Conditions	Clothing
Gardeners No. 1	Aug.	4	8	1	7	16–35	Weeding, pruning, digging a trench	6 of 8 long pants, 7 of 8 short sleeves, 1 sleeveless, socks, shoes, intermittent use of gloves
Gardeners No. 2	Aug.	4	7	2	5	26–52	Weeding, pruning, digging a trench, picking fruit, cleaning	3 of 7 long pants, 5 of 7 short sleeves, 1 sleeveless, socks, shoes, no gloves
Rugby No. 1	Mar.	1.75	8	8	0	20–22	Mixed grass-bare wet field	All in short sleeve shirts, shorts, variable sock lengths
Rugby No. 2	July	2	8	8	0	23–33	Grass field (80% of time) and all-weather field (mix of gravel, sand, and clay) (20% of time)	All in shorts, 7 of 8 in short sleeve shirts, 6 of 8 in low socks
Rugby No. 3	Sept	2.75	7	7	0	24–30	Compacted , mixed grass and bare earth field	All short pants, 7 of 8 short or rolled up sleeves, socks, shoes
Archeologists	July	11.5	7	3	4	16–35	Digging with trowel, screening dirt, sorting	6 of 7 short pants, all short sleeves, 3 no shoes, or socks, 2 sandals
Construction Workers	Sept.	8	8	8	0	21–30	Mixed bare earth and concrete surfaces, dust and debris	5 of 8 pants, 7 of 8 short sleeves, all socks and shoes
Utility Workers No. 1	July	9.5	5	5	0	24–45	Cleaning, fixing mains, excavation (backhoe and shovel)	All long pants, short sleeves, socks, boots, gloves sometimes
Utility Workers No. 2	Aug.	9.5	6	6	0	23–44	Cleaning, fixing mains, excavation (backhoe and shovel)	All long pants, 5 of 6 short sleeves, socks, boots, gloves sometimes
Equip. Operators No. 1	Aug.	8	4	4	0	21–54	Earth scraping with heavy machinery, dusty conditions	All long pants, 3 of 4 short sleeves, socks, boots, 2 of 4 gloves
Equip. Operators No. 2	Aug.	8	4	4	0	21–54	Earth scraping with heavy machinery, dusty conditions	All long pants, 3 of 4 short sleeves, socks, boots, 1 gloves
Farmers No. 1	May	2	4	2	2	39–44	Manual weeding, mechanical cultivation	All in long pants, heavy shoes, short sleeve shirts, no gloves
Farmers No. 2	July	2	6	4	2	18–43	Manual weeding, mechanical cultivation	2 of 6 short, 4 of 6 long pants, 1 of 6 long sleeve shirt, no gloves
Reed gatherers	Aug.	2	4	0	4	42–67	Tidal flats	2 of 4 short sleeve shirts/knee length pants, all wore shoes
Kids-in mud No. 1	Sept	0.17	6	5	1	9–14	Lake shoreline	All in short sleeve T-shirts, shorts, barefoot
Kids in mud No. 2	Sept.	0.33	6	5	1	9–14	Lake shoreline	All in short sleeve T-shirts, shorts, barefoot

[a] Number of subjects.

Table A-2. Estimates of soil loading on skin in different body regions resulting from various activities (EPA 1997)

Activity	N[a]	Soil loading (mg cm^{-2}) Geometric mean (geometric standard deviation)				
		Hands	Arms	Legs	Face	Feet
Indoor						
Tae Kwon Do	7	0.0063	0.0019	0.0020		0.0022
		(1.9)	(4.1)	(2.0)		(2.1)
Greenhouse Workers	2	0.043	0.0064	0.0015	0.0050	
Indoor Kids No. 1	4	0.0073	0.0042	0.0041		0.012
		(1.9)	(1.9)	(2.3)		(1.4)
Indoor Kids No. 2	6	0.014	0.0041	0.0031		0.0091
		(1.5)	(2.0)	(1.5)		(1.7)
Daycare Kids No. 1a	6	0.11	0.026	0.030		0.079
		(1.9)	(1.9)	(1.7)		(2.4)
Daycare Kids No. 1b	6	0.15	0.031	0.023		0.13
		(2.1)	(1.8)	(1.2)		(1.4)
Daycare Kids No. 2	5	0.073	0.023	0.011		0.044
		(1.6)	(1.4)	(1.4)		(1.3)
Daycare Kids No. 3	4	0.036	0.012	0.014		0.0053
		(1.3)	(1.2)	(3.0)		(5.1)
Outdoor						
Soccer No. 1	8	0.11	0.011	0.031	0.012	
		(1.8)	(2.0)	(3.8)	(1.5)	
Soccer No. 2	8	0.035	0.0043	0.014	0.016	
		(3.9)	(2.2)	(5.3)	(1.5)	
Soccer No. 3	7	0.019	0.0029	0.0081	0.012	
		(1.5)	(2.2)	(1.6)	(1.6)	
Groundskeepers No. 1	2	0.15	0.005		0.0021	0.018
Groundskeepers No. 2	5	0.098	0.0021	0.0010	0.010	
		(2.1)	(2.6)	(1.5)	(2.0)	
Groundskeepers No. 3	7	0.030	0.0022	0.0009	0.0044	0.0040
		(2.3)	(1.9)	(1.8)	(2.6)	
Groundskeepers No. 4	7	0.045	0.014	0.0008	0.0026	0.018
		(1.9)	(1.8)	(1.9)	(1.6)	--
Groundskeepers No. 5	8	0.032	0.022	0.0010	0.0039	
		(1.7)	(2.8)	(1.4)	(2.1)	
Landscape/Rockery	4	0.072	0.030		0.0057	
		(2.1)	(2.1)		(1.9)	
Irrigation Installers	6	0.19	0.018	0.0054	0.0063	
		(1.6)	(3.2)	(1.8)	(1.3)	

Table is continued on following page.

Table A-2. Estimates of soil loading on skin in different body regions resulting from various activities (EPA 1997) (continued)

		Soil loading (mg cm^{-2}) Geometric mean (geometric standard deviation)				
Activity	N[a]	Hands	Arms	Legs	Face	Feet
Gardeners No. 1	8	0.20 (1.9)	0.050 (2.1)	0.072 --	0.058 (1.6)	0.17 --
Gardeners No. 2	7	0.18 (3.4)	0.054 (2.9)	0.022 (2.0)	0.047 (1.6)	0.26 --
Rugby No. 1	8	0.40 (1.7)	0.27 (1.6)	0.36 (1.7)	0.059 (2.7)	
Rugby No. 2	8	0.14 (1.4)	0.11 (1.6)	0.15 (1.6)	0.046 (1.4)	
Rugby No. 3	7	0.049 (1.7)	0.031 (1.3)	0.057 (1.2)	0.020 (1.5)	
Archeologists	7	0.14 (1.3)	0.041 (1.9)	0.028 (4.1)	0.050 (1.8)	0.24 (1.4)
Construction Workers	8	0.24 (1.5)	0.098 (1.5)	0.066 (1.4)	0.029 (1.6)	
Utility Workers No. 1	5	0.32 (1.7)	0.20 (2.7)		0.10 (1.5)	
Utility Workers No. 2	6	0.27 (2.1)	0.30 (1.8)		0.10 (1.5)	
Equip. Operators No. 1	4	0.26 (2.5)	0.089 (1.6)		0.10 (1.4)	
Equip. Operators No. 2	4	0.32 (1.6)	0.27 (1.4)		0.23 (1.7)	
Farmers No. 1	4	0.41 (1.6)	0.059 (3.2)	0.0058 (2.7)	0.018 (1.4)	
Farmers No. 2	6	0.47 (1.4)	0.13 (2.2)	0.037 (3.9)	0.041 (3.0)	
Reed gatherers	4	0.66 (1.8)	0.036 (2.1)	0.16 (9.2)		0.63 (7.1)
Kids-in mud No. 1	6	35 (2.3)	11 (6.1)	36 (2.0)		24 (3.6)
Kids in mud No. 2	6	58 (2.3)	11 (3.8)	9.5 (2.3)		6.7 (12.4)

[a] Number of subjects.

Table A-3. Average soil loading on skin and clothing of fully equipped military personnel while performing combat crawling in different environments (Black 1962)

	Mass loading (mg cm^{-2})			
	Bare soil		Clipped dry grass	
Location	Skin	Clothes	Skin	Clothes
Neck, side	0.05	0.6	0.04	0.6
Neck, back	0.05	4	0.04	0.9
Wrist	0.1	1	0.1	2
Inside elbow	0.04	0.5	0.02	0.4
Below armpit	0.02	0.5	0.01	0.5
Chest	0.03	1	0.04	1
Back	0.04	5	0.02	1
Belt, front	0.03	5	0.03	2
Belt, back	0.01	1	0.01	0.6
Groin	0.04	5	0.02	2
Ankle	0.01	0.5	0.01	0.4
Knee	----	13	----	5
Elbow	----	8	----	1
Geometric mean	0.031	1.4[a]	0.024	0.9[a]

[a] Mass loadings on elbow and knee were not used in estimating geometric mean of loading on clothing, because elbows and knees support the body during combat crawling and, thus, clothing in those areas is more heavily loaded with soil than clothing in other areas.

Table A-4. Variability of soil loading on skin (mg cm^{-2}) of fully equipped military personnel while performing combat crawling in different environments (Black 1962)

	Bare soil 250 ft[a]		Bare soil 500 ft[a]		Clipped grass 250 ft[a]		Clipped grass 500 ft[a]	
	Median	GSD	Median	GSD	Median	GSD	Median	GSD
Neck, side	0.062	4.0	0.034	2.0	0.023	3.0	0.081	2.1
Neck, back	0.062	1.9	0.052	2.1	0.024	5.0	0.13	4.6
Wrist, left	0.124	2.4	0.124	2.4	0.065	1.5	0.20	3.4
Wrist, right	0.078	3.0	0.093	2.3	0.065	2.3	0.30	5.0
Inside elbow, left	0.055	2.6	0.023	1.7	0.016	2.3	0.037	2.4
Inside elbow, right	0.055	2.4	0.029	2.8	0.014	2.2	0.063	4.4
Below armpit, left	0.022	2.5	0.012	1.6	0.009	1.7	0.025	4.4
Below armpit, right	0.023	2.1	0.010	1.5	0.008	2.3	0.024	3.4
Chest	0.033	1.8	0.023	1.8	0.023	2.1	0.095	4.0
Back	0.046	2.3	0.037	2.5	0.016	3.3	0.031	3.2
Belt, front	0.039	3.3	0.018	2.6	0.022	3.4	0.179	16.6
Belt, back	0.013	1.9	0.009	2.3	0.005	3.2	0.016	2.9
Groin, left	0.034	2.5	0.049	1.6	0.016	2.8	0.069	6.0
Groin. Right	0.034	1.9	0.055	2.1	0.020	2.9	0.066	5.2
Ankle, left	0.015	1.8	0.007	1.6	0.006	2.6	0.019	3.3
Ankle, right	0.015	2.3	0.010	1.5	0.005	1.5	0.017	3.7

[a] Type of terrain and length of combat crawling.

Table A-5. Variability of soil loading on clothing (mg cm^{-2}) of fully equipped military personnel while performing combat crawling in different environments (Black 1962)

	Bare soil 250 ft[a]		Bare soil 500 ft[a]		Clipped grass 250 ft[a]		Clipped grass 500 ft[a]	
	Central	GSD	Central	GSD	Central	GSD	Central	GSD
Neck, side	NA[b]	NA	0.64	3.01	0.51	2.19	0.90	2.53
Neck, back	NA	NA	3.45	3.21	0.68	2.53	1.53	2.44
Wrist, left	NA	NA	0.68	4.28	1.53	2.07	1.96	2.93
Wrist, right	NA	NA	0.72	4.27	1.53	1.84	2.09	1.51
Inside elbow, left	NA	NA	0.81	2.19	0.24	4.22	0.68	1.55
Inside elbow, right	NA	NA	0.36	3.69	0.34	2.13	0.73	1.70
Below armpit, left	NA	NA	0.30	3.64	0.40	2.01	0.52	1.93
Below armpit, right	NA	NA	0.57	1.59	0.45	1.79	0.81	1.75
Chest	NA	NA	1.08	1.64	1.08	2.85	1.84	2.36
Back	NA	NA	NA	NA	0.68	2.93	NA	NA
Belt, front	NA	NA	3.26	3.39	1.93	4.03	1.92	3.42
Belt, back	NA	NA	1.15	3.29	0.43	2.68	0.86	1.99
Groin, left	NA	NA	3.87	1.50	1.62	3.38	2.11	1.65
Groin. Right	NA	NA	NA	NA	2.05	2.39	2.05	1.42
Ankle, left	NA	NA	0.86	1.79	0.48	2.19	0.73	3.04
Ankle, right	NA	NA	0.68	2.19	0.30	2.76	NA	NA

[a] Type of terrain and length of combat crawling.

[b] NA – not available; data could not be read from copy of graphs from Black (1962).

A.2 Surface Area of Skin

To estimate interception and retention fractions (r) of particles incident on the body surface using results of the volcanic ash studies in Costa Rica, estimates of the surface area of the region of skin on which dermal contamination was assessed are needed [Section 3.2, eq. (3-3)]. This section provides data on the surface area of the total body and specific body regions.

ICRP Publication 23 (ICRP 1975) recommends a reference total surface area of the body of 18,000 cm^2 for adult males and 16,000 cm^2 for adult females. Rough estimates of the surface area in other regions of the body can be obtained by applying the “rule of nines.” According to this rule, the head and neck represent 9% of the total surface area, upper limbs represent 9% each, lower limbs 18% each, and the front and the back of the trunk 18% each. The perineum and the outstretched palm and fingers each represent 1% of the total body area.

Studies to estimate the surface area of skin are reviewed in EPA’s Exposure Factors Handbook (EPA 1997). EPA’s findings indicate a total surface area of 19,400 cm^2 for adult males and 16,900 cm^2 for adult females. Data on population-averaged surface areas in different regions of the body for adults are provided in Table A-6, and percentages of the total surface area for these regions are provided in Table A-7.

The surface area of the whole body can be customized for a given individual using that individual’s height and weight:

$$SA = a_0 \cdot H^{a_1} \cdot w^{a_2} \qquad \text{(A-1)}$$

where

SA	=	surface area of total body (m^2)
H	=	height (cm),
w	=	weight (kg), and
a_0, a_1, a_2	=	empirical coefficients.

Values of the coefficients a_0, a_1, and a_2 recommended by various investigators are given in Table A-8. Once the surface area of the total body is estimated, the surface area of various regions of the body can be estimated using the percentages in Table A-7.

Table A-6. Surface area of various body regions (m^2) in adults (EPA 1997)

	Males					Females				
	N[a]	Mean	SD[b]	Min.	Max.	N[a]	Mean	SD[b]	Min.	Max.
Head	32	0.118	0.0160	0.090	0.161	57	0.110	0.00625	0.0953	0.127
Trunk incl. neck	32	0.569	0.104	0.306	0.893	57	0.542	0.0712	0.437	0.867
Upper extremities	48	0.319	0.0461	0.169	0.429	57	0.276	0.0241	0.215	0.333
Arms	32	0.228	0.0374	0.109	0.292	13	0.210	0.0129	0.193	0.235
Upper arms	6	0.143	0.0143	0.122	0.156	-	-	-	-	-
Forearms	6	0.114	0.0127	0.0945	0.136	-	-	-	-	-
Hands	32	0.084	0.0127	0.0596	0.113	12	0.0746	0.00510	0.0639	0.0824
Lower extremities	48	0.636	0.0994	0.283	0.868	57	0.626	0.0675	0.492	0.809
Legs	32	0.505	0.0885	0.221	0.656	13	0.488	0.0515	0.423	0.585
Thighs	32	0.198	0.1470	0.128	0.403	13	0.258	0.0333	0.258	0.360
Lower legs	32	0.207	0.0379	0.093	0.296	13	0.194	0.0240	0.165	0.229
Feet	32	0.112	0.0177	0.0611	0.156	13	0.0975	0.00903	0.0834	0.115
TOTAL		1.94[c]	0.00374	1.66[d]	2.28[d]		1.69[c]	0.00374	1.45[d]	2.09[d]

[a] Number of observations.

[b] Standard deviation.

[c] Median.

[d] 5^{th} and 95^{th} percentiles.

Table A-7. Percent of total body surface area in various body regions in adults (EPA 1997)

	Males					Females				
	N[a]	Mean	SD[b]	Min.	Max.	N[a]	Mean	SD[b]	Min.	Max.
Head	32	7.8	1.0	6.1	10.6	57	7.1	0.6	5.6	8.1
Trunk (incl. neck)	32	35.9	2.1	30.5	41.4	57	34.8	1.9	32.8	41.7
Upper extremities	48	18.8	1.1	16.4	21.0	57	17.9	0.9	15.6	19.9
Arms	32	14.1	0.9	12.5	15.5	13	14.0	0.6	12.4	14.8
Upper arms	6	7.4	0.5	6.7	8.1	-	-	-	-	-
Forearms	6	5.9	0.3	5.4	6.3	-	-	-	-	-
Hands	32	5.2	0.5	4.6	7.0	12	5.1	0.3	4.4	5.4
Lower extremities	48	37.5	1.9	33.3	41.2	57	40.3	1.6	36.0	43.2
Legs	32	31.2	1.6	26.1	33.4	13	32.4	1.6	29.8	35.3
Thighs	32	18.4	1.2	15.2	20.2	13	19.5	1.1	18.0	21.7
Lower legs	32	12.8	1.0	11.0	15.8	13	12.8	1.0	11.4	14.9
Feet	32	7.0	0.5	6.0	7.9	13	6.5	0.3	6.0	7.0

[a] Number of observations.

[b] Standard of deviation.

Table A-8. Coefficients in empirical model to estimate surface area of total body based on individual's height and weight[a]

Study	No. of persons	a_0	a_1	a_2	*SA* Reference Man (cm^2)[b]
All ages					
DuBois and DuBois (1916)	9	0.00718	0.725	0.425	18,100
Boyd (1935)	231	0.0179	0.500	0.484	18,200
Haycock et al. (1978)	81	0.0243	0.396	0.538	18,300
Gehan and George (1970)	401	0.0235	0.422	0.515	18,300
Adults of age ≥ 20					
Gehan and George (1970)	30	0.0155	0.545	0.463	18,100

[a] Coefficients are used in eq. (A-1).

[b] Surface area of total body for ICRP's Reference Man (ICRP 1975) of weight 70 kg and height 170 cm estimated using eq. (A-1) and coefficients in this table.

A.3 Resuspension Factors

This section presents a summary of measured resuspension factors that are relevant to estimation of doses to skin from dermal contamination and contamination of clothing following resuspension of radionuclides from the ground surface. Resuspension factors associated with mechanical stresses are summarized in Table A-9, and resuspension factors associated with winds are summarized in Table A-10. All data in these tables were obtained at sites where nuclear weapons were tested.

Table A-9. Summary of resuspension factors associated with mechanical stresses at sites where nuclear weapons were tested[a]

Location	Source material	Resuspension stress[b]	Resuspension factor (m^{-1})
Maralinga, Australia[c]	Fallout	Road survey at 1–2 days	$1 \times 10^{-8} - 2 \times 10^{-6}$
		Cab of landrover, 5th hour	6.4×10^{-5}
		Cab of landrover, 18th hour[d]	2.5×10^{-5}
	Uranium	Dust stirred, height of 0.3 m	1×10^{-3}
	Plutonium	Vehicle dust, height of 0.3 m[e]	$3 \times 10^{-4} - 7 \times 10^{-4}$
		Pedestrian dust, height of 0.3 m	$1.5 \times 10^{-6} - 3 \times 10^{-4}$
Nevada Test Site[f]	Plutonium	Extensive vehicular traffic	7×10^{-5}
Monte Bello Islands, Australia[c]	Fallout	Road survey from back of landrover	
		4th day	$8 \times 10^{-7} - 3 \times 10^{-5}$
		7th day[g]	$6 \times 10^{-7} - 4 \times 10^{-6}$
		At tail board	
		7th day	$1.6 \times 10^{-5} - 3.1 \times 10^{-5}$
Australian desert, "Totem", 1953[c]	Fallout	Walking survey	3×10^{-7}
		Vehicle survey, at tailboard	2×10^{-6}

[a] Data obtained from summary of measurements given in Table 12.9 of Sehmel (1984), except as noted.

[b] Reported times are times after detonation that produced fallout for which resuspension factor was measured.

[c] Measurements reported by Stewart (1967).

[d] Time after detonation of 8 hours reported by Sehmel (1984) appears to be erroneous.

[e] Lower bound of resuspension factor is value given by Stewart (1967); value reported by Sehmel (1984) is 3×10^{-7} m^{-1}.

[f] Measurement reported by Langham (1971).

[g] Lower bound of resuspension factor is value given by Stewart (1967); value reported by Sehmel (1984) is 7×10^{-7} m^{-1}.

Table A-10. Summary of resuspension factors associated with winds at sites where nuclear weapons were tested[a]

Location	Source material	Wind conditions	Resuspension factor (m^{-1})
Maralinga, Australia[b]	Uranium	Wind speed < 5 m s^{-1}	
		Height of 0.3 m	3×10^{-4}
		Height of 0.6 m	1×10^{-5}
Monte Bello Islands, Australia; hurricane trials[b]	Fallout	Wind speed < 5 m s^{-1}	
		16-m source, lightly vegetated sand and rock[c]	$1 \times 10^{-6} – 8 \times 10^{-5}$
		Near tower shot[d]	$1 \times 10^{-8} – 1 \times 10^{-6}$
		Near road, no disturbance	$1 \times 10^{-8} – 1.5 \times 10^{-6}$
Nevada Test Site, GMX[e]	Plutonium	Wind speed not specified	
		Near center	3×10^{-10}
		Near edge	2×10^{-9}
Nevada Test Site[f]	Plutonium	Wind speed not specified	
		Dusty rural air	7×10^{-6}
Nevada Test Site[g]	^{181}W	Wind speed not specified	$10^{-7} – 6 \times 10^{-5}$

[a] Data obtained from summary of measurements given in Table 12.7 of Sehmel (1984), except as noted.

[b] Measurements reported by Stewart (1967).

[c] Upper bound of resuspension factor is value given by Stewart (1967); value reported by Sehmel (1984) is 1×10^{-5} m^{-1}.

[d] Upper bound of resuspension factor is value given by Stewart (1967); value reported by Sehmel (1984) is 2×10^{-7} m^{-1}.

[e] Measurements reported by Anspaugh (1975).

[f] Measurements reported by Langham (1971).

[g] Measurements reported by Anspaugh (1970).

A.4 References

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APPENDIX B

ALTERNATIVE APPROACH TO ESTIMATING DOSES TO SKIN FROM DERMAL CONTAMINATION BY RESUSPENDED MATERIAL

Section 3.3 presents an approach to estimating doses to skin from dermal contamination by resuspended material that uses a differential equation in which the rate of change of the activity concentration on skin is calculated as the rate at which radioactive material is deposited on skin per unit area minus the rate at which the deposited material is lost from skin.

Analysts at SAIC[30] developed an alternative approach to estimating doses to skin from dermal contamination that could be more easily implemented using Mathcad computer software.[31] The alternative approach uses an integral equation rather than a differential equation. This appendix describes SAIC's alternative approach. The particular approach presented below applies to deposition on skin of material resuspended by winds. As discussed in Section 3.3.3, the approach can be adapted to apply to resuspension by human activities by using a deposition velocity (V_D) instead of the wind speed (V_W). As indicated by the following derivation, SAIC's alternative approach leads to the same equation for the total dose during and after deposition onto skin as was obtained in Section 3.3.2.2.

In the integral-equation approach used by SAIC, the activity concentration of resuspended radionuclides that are deposited and retained on skin during an infinitesimal time interval (t, t+dt) is calculated as $(C_{gs}^{0} \cdot T_0^{+x} \cdot RF \cdot V_W \cdot AR_f \cdot \mathrm{d}t)$, where C_{gs}^{0} is the total activity concentration of all radionuclides in fallout on the ground surface at time T_0 after a detonation when deposition of resuspended material onto skin begins, RF is the resuspension factor, V_W is the wind speed, and AR_f is the effective interception and retention fraction described in Section 3.2. The activity of radionuclides on skin during this time interval is assumed to decay with time as τ^{-x}, where $\tau \geq t$ and x is a constant.

Contamination of skin by deposition of resuspended material is assumed to start at time T_0, continue for a period ΔT_{dep}, and cease at time T_{dep}. After deposition ceases, skin is assumed to remain contaminated for an additional post-deposition period ΔT_{post} until the next shower. Skin is assumed to be irradiated continuously for a period $\Delta T_{ex} = \Delta T_{dep} + \Delta T_{post}$, during which the dose rate can vary with time. Exposure is assumed to cease at time $T_{\mathrm{ex}} = T_{dep} + \Delta T_{post}$.

[30] Klemm J., personal communication (2004); Raine D., personal communication (December 2004).
[31] http://www.mathcad.com.

The dose from decay of radioactive material deposited on skin is obtained by integrating the dose rate from the time of deposition (t) until the time of decontamination (T_{ex}). Doses from all depositions that occur from the time deposition begins (T_0) to the time deposition ceases (T_{dep}) are summed (i.e., integrated) to obtain a total dose:

$$D = \int_{T_0}^{T_{dep}} \int_{t}^{T_{ex}} \left[C_{gs}^0 \cdot T_0^{+x} \cdot RF \cdot V_W \cdot AR_f \cdot \tau^{-x} \cdot DRF_{skin} \right] \mathrm{d}\tau\, \mathrm{d}t \tag{B-1}$$

Equation (B-1) can be integrated to obtain:

$$\begin{aligned} D &= C_{gs}^0 \cdot T_0^{+x} \cdot RF \cdot V_W \cdot AR_f \cdot DRF_{skin} \int_{T_0}^{T_{dep}} \int_{t}^{T_{ex}} \tau^{-x}\, \mathrm{d}\tau\, \mathrm{d}t \\ &= C_{gs}^0 \cdot T_0^{+x} \cdot RF \cdot V_W \cdot AR_f \cdot DRF_{skin} \int_{T_0}^{T_{dep}} \frac{\tau^{-(x-1)}\Big|_{t}^{T_{ex}}}{-(x-1)}\, \mathrm{d}t \\ &= C_{gs}^0 \cdot T_0^{+x} \cdot RF \cdot V_W \cdot AR_f \cdot DRF_{skin} \int_{T_0}^{T_{dep}} \frac{t^{-(x-1)} - T_{ex}^{-(x-1)}}{(x-1)}\, \mathrm{d}t = \\ &= C_{gs}^0 \cdot T_0^{+x} \cdot RF \cdot V_W \cdot AR_f \cdot DRF_{skin} \cdot \frac{1}{(x-1)} \left[\frac{t^{-(x-2)}\Big|_{T_0}^{T_{dep}}}{-(\mathrm{x}-2)} - t\Big|_{T_0}^{T_{dep}} \cdot T_{ex}^{-(x-1)} \right] \end{aligned} \tag{B-2}$$

The resulting equation for the total dose is:

$$\begin{aligned} D = \frac{C_{gs}^0 \cdot T_0^{+x} \cdot RF \cdot V_W \cdot AR_f \cdot DRF_{skin}}{(x-1)(2-x)} \times \\ \left[T_{dep}^{-(x-2)} - (2-x) \cdot (T_{dep} - T_0) \cdot T_{ex}^{-(x-1)} - T_0^{-(x-2)} \right] \end{aligned} \tag{B-3}$$

The solution in eq. (B-3) represents the total dose received from the time deposition onto skin begins until contamination is assumed to be removed by showering. When the wind velocity, V_W, is substituted for the deposition velocity, V_D, and the units conversion factor of 0.36 discussed following eq. (3-8) in Section 3.3.2.2, which is derived on the basis of assumed units for each parameter, is taken into account, this equation is identical to eq. (3-27) that was derived in Section 3.3.2.2 using a differential-equation approach.

If decontamination (e.g., by showering) takes places at the time deposition ceases (i.e., $T_{dep} = T_{ex}$), the solution represents the dose during the period of deposition. This solution, which is given in eq. (B-4) below, is to the same as eq. (3-19) in Section 3.3.2.2:

$$D_{dep} = \frac{C_{gs}^{0} \cdot T_0^{+x} \cdot RF \cdot V_W \cdot AR_f \cdot DRF_{skin}}{(x-1)(2-x)} \times \left[(x-1) \cdot T_{dep}^{-(x-2)} + (2-x) \cdot T_0 \cdot T_{dep}^{-(x-1)} - T_0^{-(x-2)} \right] \tag{B-4}$$

Thus, the differential-equation approach presented in this report and the integral-equation approach used by SAIC produce identical results. A potential advantage of our approach is that it provides estimates of the activity concentration of radionuclides on skin as a function of time during the deposition period and after deposition ceases, and it provides separate estimates of doses to skin during the deposition period and after deposition ceases until decontamination.

APPENDIX C

PARAMETER VALUES USED TO EVALUATE IMPORTANCE OF DOSES TO SKIN FROM DERMAL CONTAMINATION

Calculations summarized in Section 6 of the main report investigate conditions under which dermal contamination by beta-emitting radionuclides should be considered important in estimating the total dose to skin. That investigation involves a comparison of doses to skin from dermal contamination with doses from exposure to beta emitters on the ground surface in various exposure scenarios. If the dose to skin from dermal contamination in a given scenario is at least a substantial fraction of the dose from beta emitters on the ground surface, we consider that dermal contamination is an important contributor to the total dose to skin in that scenario. The evaluation in Section 6 does not take into account the potential importance of incomplete removal of radionuclides from skin by showering, which results in increases in dose from dermal contamination but does not affect doses from ground-surface exposure.

Tables C-1 to C-6 provide point (deterministic) estimates of parameter values that were used in calculations to evaluate the importance of doses to skin from dermal contamination relative to doses from exposure to a contaminated ground surface in various scenarios in which dermal contamination results from descending fallout (Table C-1), resuspension by vehicular traffic (Table C-2), wind-driven resuspension (Tables C-3 and C-4), and resuspension by the blast wave or thermal pulse produced in a nuclear detonation (Tables C-5 and C-6). Calculations assume exposure at 2 days or 4 years after a detonation. Only in the scenario for wind-driven resuspension is there a difference in parameter values at the two times; all other time-dependent effects involve differences in the particular radionuclides that contribute significantly to doses from dermal contamination and ground-surface exposure. Calculations also assume exposure at locations near to and far from ground zero to investigate the effect of particle size.

Table C-1. Parameter values used to estimate doses to skin from exposure to descending fallout[a]

			NTS, close to ground zero		Pacific, far from ground zero	
Parameter name	Symbol	Units	Face	Arms	Face	Arms
Interception and retention fraction	r	unitless	0.015	0.06	0.015	0.06
Particle-size adjustment factor	PS_a	unitless	1	1	1.3	1.3
Enhancement due to moisture	EM	unitless	0.75	0.75	1.15	1.15
Enrichment of specific activity	EF	unitless	2.0	2.0	1.3	1.3
Activity-weight adjustment factor	AW	unitless	0.1	0.1	1	1
Skin-depth modification factor	$SDMF$	unitless	1.3	0.9	1.3	0.9
Time to first shower	ΔT_{post}	h	12	12	12	12
Duration of exposure to radionuclides on ground surface	ΔT_{ground}	h	4	4	8	8

[a] Deposition on skin is assumed to be acute event that occurs instantaneously.

Table C-2. Parameter values used to estimate doses to skin from exposure to radionuclides resuspended by vehicular traffic[a]

Parameter name	Symbol	Units	NTS, close to ground zero	
			Face	Arms
Interception and retention fraction	r	unitless	0.015	0.06
Particle-size adjustment factor	PS_a	unitless	1.3	1.3
Enhancement due to moisture	EM	unitless	0.75	0.75
Enrichment of specific activity	EF	unitless	1.3	1.3
Activity-weight adjustment factor	AW	unitless	1	1
Skin-depth modification factor	$SDMF$	unitless	1.3	0.9
Resuspension factor	RF	m^{-1}	2×10^{-5}	2×10^{-5}
Deposition velocity	V_D	$m\ s^{-1}$	1	1
Duration of deposition onto skin	ΔT_{dep}	h	4	4
Time to first shower	ΔT_{post}	h	8	8
Duration of exposure to radionuclides on ground surface	ΔT_{ground}	h	4	4

[a] Exposure is assumed to occur while marching behind vehicles; parameter values apply at any time after a detonation.

Table C-3. Parameter values used to estimate doses to skin from exposure to radionuclides resuspended by winds at times shortly after detonation[a]

Parameter name	Symbol	Units	NTS, close to ground zero		Pacific, far from ground zero	
			Face	Arms	Face	Arms
Interception and retention fraction	r	unitless	0.015	0.06	0.015	0.06
Particle-size adjustment factor	PS_a	unitless	1.3	1.3	1.3	1.3
Enhancement due to moisture	EM	unitless	0.75	0.75	1.15	1.15
Enrichment of specific activity	EF	unitless	1.3	1.3	1.3	1.3
Activity-weight adjustment factor	AW	unitless	1	1	1	1
Skin-depth modification factor	$SDMF$	unitless	1.3	0.9	1.3	0.9
Resuspension factor	RF	m^{-1}	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}
Wind velocity	V_W	$m\ s^{-1}$	4	4	5	5
Duration of deposition onto skin	ΔT_{dep}	h	8	8	8	8
Time to first shower	ΔT_{post}	h	4	4	4	4
Duration of exposure to radionuclides on ground surface	ΔT_{ground}	h	8	8	8	8

[a] Exposure is assumed to occur within a few days after a detonation.

Table C-4. Parameter values used to estimate doses to skin from exposure to radionuclides resuspended by winds at times long after detonation[a]

Parameter name	Symbol	Units	NTS, close to ground zero		Pacific, far from ground zero	
			Face	Arms	Face	Arms
Interception and retention fraction	r	unitless	0.015	0.06	0.015	0.06
Particle-size adjustment factor	PS_a	unitless	1.3	1.3	1.3	1.3
Enhancement due to moisture	EM	unitless	0.75	0.75	1.15	1.15
Enrichment of specific activity	EF	unitless	1.3	1.3	1.3	1.3
Activity-weight adjustment factor	AW	unitless	1	1	1	1
Skin-depth modification factor	$SDMF$	unitless	1.3	0.9	1.3	0.9
Resuspension factor	RF	m^{-1}	3×10^{-8}	3×10^{-8}	3×10^{-8}	3×10^{-8}
Wind velocity	V_W	$m\ s^{-1}$	4	4	5	5
Duration of deposition onto skin	ΔT_{dep}	h	8	8	8	8
Time to first shower	ΔT_{post}	h	4	4	4	4
Duration of exposure to radionuclides on ground surface	ΔT_{ground}	h	8	8	8	8

[a] Exposure is assumed to occur at times of a few years after a detonation.

Table C-5. Parameter values used to estimate doses to skin from exposure to radionuclides resuspended by blast wave in detonation at NTS[a]

			Forward observers (large particles only)		Forward observers and maneuver troops (small particles only)	
Parameter name	Symbol	Units	Face	Arms	Face	Arms
Interception and retention fraction	*R*	unitless	0.015	0.06	0.015	0.06
Particle-size adjustment factor	PS_a	unitless	0.8	0.8	1.3	1.3
Enhancement due to moisture	*EM*	unitless	0.75	0.75	0.75	0.75
Enrichment of specific activity	*EF*	unitless	2.5	2.5	1.3	1.3
Activity-weight adjustment factor	*AW*	unitless	0.03	0.03	1	1
Skin-depth modification factor	*SDMF*	unitless	1.3	0.9	1.3	0.9
Resuspension factor	*RF*	m^{-1}	1.0×10^{-5}	1.0×10^{-5}	1×10^{-7}	1×10^{-7}
Deposition velocity	V_D	$m\ s^{-1}$			1	1
Height of cloud of resuspended material	*H*	m	30	30		
Duration of deposition onto skin	ΔT_{dep}	h	[b]	[b]	2	2
Time to first shower	ΔT_{post}	h	12	12	10	10
Duration of exposure to radionuclides on ground surface	ΔT_{ground}	h	2	2	2	2

[a] Parameter values apply at any time after a previous detonation.

[b] Deposition of large particles is assumed to occur instantaneously.

Table C-6. Parameter values used to estimate doses to skin from exposure to radionuclides resuspended by thermal pulse in detonation at NTS[a]

Parameter name	Symbol	Units	Maneuver troops (small particles only)	
			Face	Arms
Interception and retention fraction	r	unitless	0.015	0.06
Particle-size adjustment factor	PS_a	unitless	1.3	1.3
Enhancement due to moisture	EM	unitless	0.75	0.75
Enrichment of specific activity	EF	unitless	1.3	1.3
Activity-weight adjustment factor	AW	unitless	1	1
Skin-depth modification factor	$SDMF$	unitless	1.3	0.9
Resuspension factor	RF	m^{-1}	1×10^{-5}	1×10^{-5}
Deposition velocity	V_D	$m\ s^{-1}$	1	1
Duration of deposition onto skin	ΔT_{dep}	h	2	2
Time to first shower	ΔT_{post}	h	10	10
Duration of exposure to radionuclides on ground surface	ΔT_{ground}	h	2	2

[a] Parameter values apply at any time after a previous detonation.

APPENDIX D

EFFECT OF INEFFICIENT SHOWERING ON DOSE TO SKIN FROM DERMAL CONTAMINATION – MODELING AND AVAILABLE DATA

This appendix presents information on the effect of inefficient showering on doses to skin from dermal contamination. Appendix D.1 presents a derivation of the model discussed in Section 3.5.2 to estimate dose from an acute deposition onto skin when showering does not remove all contamination from skin. Appendix D.2 presents and discusses data that can be used to estimate the fraction of the contamination on skin that is removed in the first and subsequent showers after an acute deposition.

D.1 Modeling of Effect of Inefficient Showering on Dose to Skin from Acute Dermal Contamination

This appendix presents a derivation of eq. (3-33) in Section 3.5.2, which gives the total dose to skin from an acute deposition of a mixture of radionuclides in fallout, taking into account the effect of inefficient showering in removing contamination from skin. An acute deposition (e.g., fallout from a nuclear weapon detonation) occurs at time T_0, the first shower occurs at time T_1, and subsequent showers occur at times T_2, T_3, …, T_N. All times are specified in hours from the time of the detonation that produced the acute deposition on skin. Derivation of eq. (3-33) involves an iterative procedure in which the dose between successive showers and the total dose from the time of deposition to the time of a given shower is modeled.

D.1.1 Period from T_0 to T_1

We first consider the dose to skin during the period from T_0 (the time of an acute deposition on skin) to T_1 (the time of the first shower). The activity concentration of radionuclides on skin due to an acute deposition at time T_0 is estimated in accordance with eq. (3-2) (Section 3.2) as:

$$C_{skin}(T_0) = C_{gs}(T_0) \cdot AR_f$$

Given this estimate of $C_{skin}(T_0)$, the concentration on skin immediately before the first shower at time T_1 is estimated as:

$$C_{skin}^{before}(T_1) = C_{skin}(T_0) \cdot T_0^{+x} \cdot T_1^{-x}$$

The first shower removes a fraction of the contamination on skin at time T_1. This fraction is given by ($\gamma_1 + \beta$), where γ_1 is the fraction removed by washing and β is the fraction removed by exfoliation of skin cells during the first shower. The parameter γ should be highest during the first shower and lower during each successive shower. The parameter β is assumed to be the same in all showers, and showering is assumed to be the only activity that removes a significant amount of contamination by exfoliation. The fraction of the contamination on skin at time T_1

that remains after the first shower then is $\alpha_1 = [1 - (\gamma_1 + \beta)]$, and the concentration on skin immediately <u>after</u> the first shower at time T_1 is estimated as:

$$C_{skin}^{after}\left(T_1\right) = \alpha_1 \cdot C_{skin}\left(T_0\right) \cdot T_0^{+x} \cdot T_1^{-x}$$

The dose received during the period from T_0 to T_1, as derived from eq. (3-6) (Section 3.2.2), is estimated as:

$$\begin{aligned} D(T_1) &= D_1 \\ &= C_{gs}^0 \cdot T_0^{+x} \cdot AR_f \cdot DRF_{skin} \cdot \frac{T_0^{-(x-1)} - T_1^{-(x-1)}}{x-1} \\ &= C_{skin}\left(T_0\right) \cdot T_0^{+x} \cdot DRF_{skin} \cdot \frac{T_0^{-(x-1)} - T_1^{-(x-1)}}{x-1} \end{aligned}$$

D.1.2 Period from T_1 to T_2

As derived in the previous section, the activity concentration of radionuclides on skin immediately after the first shower at time T_1 is estimated as:

$$C_{skin}^{after}\left(T_1\right) = \alpha_1 \cdot C_{skin}\left(T_0\right) \cdot T_0^{+x} \cdot T_1^{-x}$$

Given this estimate of $C_{skin}^{after}(T_1)$, the concentration on skin immediately before the second shower at time T_2 is estimated as:

$$\begin{aligned} C_{skin}^{before}\left(T_2\right) &= C_{skin}^{after}\left(T_1\right) \cdot T_1^{+x} \cdot T_2^{-x} \\ &= \alpha_1 \cdot C_{skin}\left(T_0\right) \cdot T_0^{+x} \cdot T_1^{-x} \cdot T_1^{+x} \cdot T_2^{-x} \\ &= \alpha_1 \cdot C_{skin}\left(T_0\right) \cdot T_0^{+x} \cdot T_2^{-x} \end{aligned}$$

The second shower removes a fraction of the contamination on skin at time T_2 given by $(\gamma_2 + \beta)$, and the fraction of the contamination at that time that remains on skin after the second shower is $\alpha_2 = [1 - (\gamma_2 + \beta)]$. The concentration on skin immediately after the second shower at time T_2 then is estimated as:

$$C_{skin}^{after}\left(T_2\right) = \alpha_2 \cdot \alpha_1 \cdot C_{skin}\left(T_0\right) \cdot T_0^{+x} \cdot T_2^{-x}$$

The dose received during the period from T_1 to T_2 is estimated as:

$$D(T_2) = C_{skin}^{after}\left(T_1\right) \cdot T_1^{+x} \cdot DRF_{skin} \cdot \frac{T_1^{-(x-1)} - T_2^{-(x-1)}}{x-1}$$
$$= \alpha_1 \cdot C_{skin}\left(T_0\right) \cdot T_0^{+x} \cdot T_1^{-x} \cdot T_1^{+x} \cdot DRF_{skin} \cdot \frac{T_1^{-(x-1)} - T_2^{-(x-1)}}{x-1}$$
$$= \alpha_1 \cdot C_{skin}\left(T_0\right) \cdot T_0^{+x} \cdot DRF_{skin} \cdot \frac{T_1^{-(x-1)} - T_2^{-(x-1)}}{x-1}$$

Using the dose received during the period from T_0 to T_1 that was derived in the previous section, the dose received during the period from T_0 to T_2 then is estimated as:

$$D_2 = D\left(T_1\right) + D\left(T_2\right)$$
$$= C_{skin}\left(T_0\right) \cdot T_0^{+x} \cdot DRF_{skin} \cdot \frac{T_0^{-(x-1)} - T_1^{-(x-1)}}{x-1} + \alpha_1 \cdot C_{skin}\left(T_0\right) \cdot T_0^{+x} \cdot DRF_{skin} \cdot \frac{T_1^{-(x-1)} - T_2^{-(x-1)}}{x-1}$$
$$= C_{skin}\left(T_0\right) \cdot T_0^{+x} \cdot DRF_{skin}\left[\frac{\mathrm{T}_0^{-(x-1)} - T_1^{-(x-1)}}{x-1} + \alpha_1 \cdot \frac{T_1^{-(x-1)} - T_2^{-(x-1)}}{x-1}\right]$$

D.1.3 Period from T_2 to T_3

The effect of inefficient showering on the dose during the period from the second shower at time T_2 to the third shower at time T_3 can be modeled by analogy with modeling of the effect during the period from the first to the second shower. As derived in the previous section, the activity concentration of radionuclides on skin immediately after the second shower at time T_2 is estimated as:

$$C_{skin}^{after}\left(T_2\right) = \alpha_2 \cdot \alpha_1 \cdot C_{skin}\left(T_0\right) \cdot T_0^{+x} \cdot T_2^{-x}$$

Given this estimate of $C_{skin}^{after}(T_2)$, the concentration on skin immediately before the third shower at time T_3 is estimated as:

$$C_{skin}^{before}\left(T_3\right) = C_{skin}^{after}\left(T_2\right) \cdot T_2^{+x} \cdot T_3^{-x}$$
$$= \alpha_2 \cdot \alpha_1 \cdot C_{skin}\left(T_0\right) \cdot T_0^{+x} \cdot T_2^{-x} \cdot T_2^{+x} \cdot T_3^{-x}$$
$$= \alpha_2 \cdot \alpha_1 \cdot C_{skin}\left(T_0\right) \cdot T_0^{+x} \cdot T_3^{-x}$$

The third shower removes a fraction of the contamination on skin at time T_3 given by (γ_3 + β), and the fraction of the contamination at that time that remains on skin after the third

shower is $\alpha_3 = [1 - (\gamma_3 + \beta)]$. The concentration on skin immediately after the third shower at time T_3 then is estimated as:

$$C_{skin}^{after}(T_3) = \alpha_3 \cdot \alpha_2 \cdot \alpha_1 \cdot C_{skin}(T_0) \cdot T_0^{+x} \cdot T_3^{-x}$$

The dose received during the period from T_2 to T_3 is estimated as:

$$\begin{aligned} D(T_3) &= C_{skin}^{after}(T_2) \cdot T_2^{+x} \cdot DRF_{skin} \cdot \frac{T_2^{-(x-1)} - T_3^{-(x-1)}}{x-1} \\ &= \alpha_2 \cdot \alpha_1 \cdot C_{skin}(T_0) \cdot T_0^{+x} \cdot T_2^{-x} \cdot T_2^{+x} \cdot DRF_{skin} \cdot \frac{T_2^{-(x-1)} - T_3^{-(x-1)}}{x-1} \\ &= \alpha_2 \cdot \alpha_1 \cdot C_{skin}(T_0) \cdot T_0^{+x} \cdot DRF_{skin} \cdot \frac{T_2^{-(x-1)} - T_3^{-(x-1)}}{x-1} \end{aligned}$$

Using equations derived in the previous two sections, the dose received during the period from T_0 to T_3 then is estimated as:

$$\begin{aligned} D_2 &= D(T_1) + D(T_2) + D(T_3) \\ &= C_{skin}(T_0) \cdot T_0^{+x} \cdot DRF_{skin} \cdot \frac{T_0^{-(x-1)} - T_1^{-(x-1)}}{x-1} + \alpha_1 \cdot C_{skin}(T_0) \cdot T_0^{+x} \cdot DRF_{skin} \cdot \frac{T_1^{-(x-1)} - T_2^{-(x-1)}}{x-1} + \\ &\qquad \alpha_2 \cdot \alpha_1 \cdot C_{skin}(T_0) \cdot T_0^{+x} \cdot DRF_{skin} \cdot \frac{T_2^{-(x-1)} - T_3^{-(x-1)}}{x-1} \\ &= C_{skin}(T_0) \cdot T_0^{+x} \cdot DRF_{skin} \left[\frac{T_0^{-(x-1)} - T_1^{-(x-1)}}{x-1} + \alpha_1 \cdot \frac{T_1^{-(x-1)} - T_2^{-(x-1)}}{x-1} + \alpha_2 \cdot \alpha_1 \cdot \frac{T_2^{-(x-1)} - T_3^{-(x-1)}}{x-1} \right] \end{aligned}$$

D.1.4 Period from T_{N-1} to T_N

Finally, we consider the effect of inefficient showering on the dose during the period from the next-to-last shower at time T_{N-1} to the last shower at time T_N. The activity concentration of radionuclides on skin is assumed to be negligible after the last shower. By analogy with previous derivations, the concentration on skin immediately after the next-to-last shower at time T_{N-1} is estimated as:

$$C_{skin}^{after}(T_{N-1}) = \alpha_{N-1} \cdot \ldots \cdot \alpha_2 \cdot \alpha_1 \cdot C_{skin}(T_0) \cdot T_0^{+x} \cdot T_{N-1}^{-x}$$

Given this estimate of $C_{skin}^{after}(T_{N-1})$, the concentration on skin immediately before the last shower at time T_N is estimated as:

$$\begin{aligned} C_{skin}^{before}(T_N) &= C_{skin}^{after}(T_{N-1}) \cdot T_{N-1}^{+x} \cdot T_N^{-x} \\ &= \alpha_{N-1} \cdot \ldots \cdot \alpha_2 \cdot \alpha_1 \cdot C_{skin}(T_0) \cdot T_0^{+x} \cdot T_{N-1}^{-x} \cdot T_{N-1}^{+x} \cdot T_N^{-x} \\ &= \alpha_{N-1} \cdot \ldots \cdot \alpha_2 \cdot \alpha_1 \cdot C_{skin}(T_0) \cdot T_0^{+x} \cdot T_N^{-x} \end{aligned}$$

The dose received during the period from T_{N-1} to T_N is estimated as:

$$\begin{aligned} D(T_N) &= C_{skin}^{after}(T_{N-1}) \cdot T_{N-1}^{+x} \cdot DRF_{skin} \cdot \frac{T_{N-1}^{-(x-1)} - T_N^{-(x-1)}}{x-1} \\ &= \alpha_{N-1} \cdot \ldots \cdot \alpha_2 \cdot \alpha_1 \cdot C_{skin}(T_0) \cdot T_0^{+x} \cdot T_{N-1}^{-x} \cdot T_{N-1}^{+x} \cdot DRF_{skin} \cdot \frac{T_{N-1}^{-(x-1)} - T_N^{-(x-1)}}{x-1} \\ &= \alpha_{N-1} \cdot \ldots \cdot \alpha_2 \cdot \alpha_1 \cdot C_{skin}(T_0) \cdot T_0^{+x} \cdot DRF_{skin} \cdot \frac{T_{N-1}^{-(x-1)} - T_N^{-(x-1)}}{x-1} \end{aligned}$$

Using equations derived in the previous sections, the dose received during the period from T_0 to T_N (i.e., from the time of an acute deposition onto skin until the time of the last shower) then is estimated as:

$$\begin{aligned} D_N &= D(T_1) + D(T_2) + D(T_3) + \ldots + D(T_N) \\ &= C_{skin}(T_0) \cdot T_0^{+x} \cdot DRF_{skin} \times \left[\frac{T_0^{-(x-1)} - T_1^{-(x-1)}}{x-1} + \alpha_1 \cdot \frac{T_1^{-(x-1)} - T_2^{-(x-1)}}{x-1} + \right. \\ &\quad \left. \alpha_2 \cdot \alpha_1 \cdot \frac{T_2^{-(x-1)} - T_3^{-(x-1)}}{x-1} + \ldots + \alpha_{N-1} \cdot \ldots \cdot \alpha_2 \cdot \alpha_1 \cdot \frac{T_{N-1}^{-(x-1)} - T_N^{-(x-1)}}{x-1} \right] \end{aligned}$$

Thus, the total dose, as given in eq. (3-33) (Section 3.5.2), is estimated as:

$$D_N = C_{skin}(T_0) \cdot T_0^{+x} \cdot DRF_{skin} \cdot \sum_{j=1}^{N} \left[\frac{T_{j-1}^{-(x-1)} - T_j^{-(x-1)}}{x-1} \left(\prod_{k=1}^{j-1} \alpha_k \right) \right]$$

D.2 Data on Removal of Skin Cells by Exfoliation and Efficiency of Washing in Removing Contamination from Skin

In models to represent the effect of inefficient showering on doses from dermal contamination developed in Section 3.5, contamination is assumed to be removed from skin by two processes: exfoliation of skin cells and washing (removal by soap and water). By assuming that exfoliation of skin cells occurs mainly as a result of scrubbing while showering, the fraction of the contamination that is removed per shower is represented by $(\beta + \gamma)$, where β is the fraction removed by exfoliation of skin cells and γ is the fraction removed by washing. The fraction of the contamination that remains on skin after a shower then is estimated as $\alpha = [1 - (\beta + \gamma)]$. This appendix presents data that can be used to estimate removal fractions of contamination from skin (fractions of contamination removed per shower) by the two processes.

D.2.1 Data on Exfoliation of Skin Cells

Data on renewal times for cells in the epidermis were reviewed in ICRP Publication 23 (ICRP 1975; Sections II.A.6.a and II.A.6.b). These data are assumed to represent turnover times of normal epidermal cells by exfoliation. Cell renewal times for the epidermis reported by ICRP (1975) include the following:

Observed Renewal Times –

- Palms, 32–36 days;
- Upper Limbs, 17 days;
- Lower Limbs, 29–30 days.

Calculated Renewal Times –

- Basal layer of scalp, 129 days;
- Abdominal skin of persons of age 0–20 y, 91 days;
- Abdominal skin of persons of age 21–40 y, 43 days.

The available data for normal skin cells evidently are limited. We also note that a turnover time as low as 7 days is representative of skin afflicted with psoriasis (Cormack 1993).

D.2.2 Data on Efficiency of Washing in Removing Contamination from Skin

In implementing the models developed in Section 3.5, the fraction of the contamination on skin that is removed by washing per shower is assumed to be highest in the first shower and to decrease with each successive shower for the first few showers. This section discusses data from various studies that can be used to estimate the fractions of contamination on skin that are removed in the first shower and subsequent showers. Relevant studies investigated the efficiency of wiping, washing or showering in removing particulate material from skin.

D.2.2.1 *General Discussion of Data and Application to Modeling of Inefficient Showering*

In all studies discussed in the following sections that investigated the amount (fraction) of contamination that was removed from skin by multiple wipes or washings, the amount removed in each wipe or washing was reported with respect to the amount of contamination on skin at the time of the *first* wipe or washing. Results in that form cannot be used directly in models developed in Section 3.5. The desired quantity for use in those models is the fraction of contamination on skin at the time of *each shower* that is removed at that time. This fraction is the parameter γ_j, where j denotes the jth shower in a succession of showers ($j = 1, \ldots, N$). In all showers after the first, γ_j does not depend on the amount of contamination on skin at the time of the first shower. In the following sections, results of removal studies are presented as reported, and those results are converted to estimates of γ_j that can be used in our models.

Consider, for example, a hypothetical study in which 100 units of contamination were present on skin at the time of the first wipe or washing, and the amounts of contamination removed in three successive wipes or washings were 50, 20, and 5 units, respectively. Reported fractions of the initial contamination removed in each wipe or washing in this example would be 0.50, 0.20, and 0.05. The sum of these fractions cannot exceed 1.0. Alternatively, the total (cumulative) amounts of contamination removed after each wipe or washing could be reported. In this case, these amounts, expressed as cumulative fractions of the initial contamination, would be 0.50, 0.70, and 0.75, where the cumulative fraction after the last wipe or washing cannot exceed 1.0. The corresponding fractions of contamination that was present at the time of each wipe or washing that was removed at that time, γ_j, in this example would be $\gamma_1 = 50/100 = 0.50$,

γ_2 = 20/50 = 0.40, and γ_3 = 5/30 = 0.17. Again, these fractions are parameters that can be used in models developed in Section 3.5. The only constraint is that γ_j cannot exceed 1.0.

D.2.2.2 *Data from Study by Boeniger*

Boeniger (2006) investigated the efficiency of commercially available surface-wipe media in removing lead dust on hands. That study involved four consecutive wipes of the palm of each hand for 30 s each after a simulated contamination with a mixture of lead oxide (PbO) dust and baby powder. All wipes were moist at the time of the first wipe, and moisture losses during the study were less than 10%. Low (200 μg) and high (3,000 μg) loadings of powder were applied over an area of about 1,060 cm^2. Sizes of dust particles were not reported.

Fractions of the initial contamination that was removed by each wipe reported by Boeniger (2006) are given in Table D-1, and the corresponding estimates of the parameter γ_j used in our models are given in Table D-2. About 52-63% of the total lead loading was removed from the palms with the first wipe, and up to about 75% removal was achieved after four successive wipes. The data on removal efficiencies of wipe media may not be representative of removal by showering, but they provide insight into the amount of dust that can be removed by wiping. Results indicate that the fraction of the initial dust loading removed by a first wipe is higher than the fraction removed by any subsequent wipe. The parameter γ_j used in our models also is seen to decrease in each successive wipe.

D.2.2.3 *Data from Study by Boeniger et al.*

In an earlier study by Boeniger et al. (2005), about 3,000 μg of lead oxide dust (PbO) was applied to the hands of a number of subjects, who then washed their hands once or twice, with or without rinse, with several commercial skin cleansers, including liquid soap and heavier industrial abrasive cleansers. A typical amount of lead that remained on the hands after washing was 400 μg, or about 13% of the amount applied before washing; i.e., about 87% of the contamination was removed. The best-performing commercial product (Ivory Liquid Soap) removed about 98% of the initial lead contamination.

The study by Boeniger et al. (2005) involved rubbing of skin on the hands in one or two washings, which is likely to be more efficient in removing contamination than washing of skin on other parts of the body during normal showering. On parts of the body other than the hands, washing during a shower could be less efficient in removing contamination, because some areas are difficult to reach and showering sometimes involves mostly rinsing, with little application of soap or vigorous rubbing.

D.2.2.4 *Data from Study by Sharp and Chapman*

Sharp and Chapman (1957) described efforts to decontaminate 82 native inhabitants of the Marshall Islands and some military personnel who were exposed to fallout from detonation of Operation CASTLE, Shot BRAVO on March 1, 1954. Sixteen of the 82 Marshallese were evacuated by airplane, and the others were evacuated by ship. After arriving at Kwajalein Atoll, all evacuees were decontaminated by showering and bathing, often repeatedly, and residual levels of contamination were monitored with hand-held survey meters, which measured external exposure rates near the body surface.

Only the monitoring data for 15 Marshallese who were evacuated by plane and showered several times at Kwajalein Atoll can be used to estimate fractions of the activity of fallout contamination on skin that was removed by successive showers. There were no measurements before the fourth shower for one individual who was evacuated by plane, and the remaining 66 individuals who were evacuated by ship showered or were hosed down with salt water several times before they were first monitored. Survey meter readings (mR h^{-1}) on March 3 for the 15 Marshallese reported by Sharp and Chapman (1957) are given in Table D-3, and the corresponding estimates of the parameter γ_j used in our models are given in Table D-4.

Data in Table D-3 were obtained under realistic conditions of contamination by descending fallout and repeated showers soon after deposition on skin. However, measured exposure rates after each shower probably included significant contributions from internally deposited radionuclides. To the extent that those contributions were significant, observed reductions in exposure rates after successive showers should underestimate fractions of the contamination on skin that was removed during each shower. In addition, native Marshallese were clothed while showering (Sharp and Chapman 1957), which could have affected removal of

contamination and measured exposure rates. It is likely that showering while clothed also resulted in underestimates of removal of contamination on skin.

Twenty-eight military personnel who were exposed to fallout from Shot BRAVO also were evacuated to Kwajalein, decontaminated by showering after arrival, and monitored. Monitoring data for those personnel are given in Table D-5. Those data probably are of limited use in estimating removal of contamination from skin. Exposure rates for many individuals, including some who did not report that they showered before evacuation, were not reduced substantially by showering at Kwajalein on March 2. For the eight individuals with exposure rates prior to the first shower on March 2 that ranged from 90 to 250 mR h^{-1}, including four individuals who reported that they showered before evacuation, the exposure rate after the first shower ranged from 4 to 15% of the exposure rate beforehand, indicating that a single shower removed between 85 and 96% of the contamination, but the exposure rate for those eight individuals was not reduced after the second and successive showers. Given the likelihood of significant internal contamination of those eight individuals, the high fractional removals after the first shower indicated by these data probably are underestimates.

Another potentially important consideration in interpreting monitoring data for native Marshallese and military personnel after Shot BRAVO is that decontamination by showering or washing probably involved more vigorous scrubbing than normal, in an effort to remove known high levels of contamination. Sharp and Chapman (1957) noted that special efforts were needed to adequately decontaminate the hair and head of Marshallese, that scrubbing of Marshallese sometimes caused tenderness and soreness on other parts of the body, and that military personnel were subjected to a thorough decontamination regime. Such deliberate actions probably removed higher fractions of contamination on skin than occurred in routine showering when high levels of contamination were not suspected. Higher removals of contamination than normal could have compensated somewhat for the likelihood that measured external exposure rates underestimated the extent of removal from skin, as noted above.

D.2.2.5 *Data from Study by Friedman*

Friedman (1958) studied the efficiency of removal of dry soil from skin of 45 volunteers by various aqueous and waterless methods. Soil was labeled with ^{140}La and was intended to

simulate radioactive fallout. The size of soil particles ranged from 1.5 μm to < 47 μm. Soil was applied on the hairless side of forearms as dust, under dry conditions, and was worked into skin with a rounded glass rod using moderate pressure. Only the aqueous methods are of interest in estimating the efficiency of showering in removing contamination. These methods included: (1) running tap water, with scrub; (2) soap (stearate salt) and water, scrub and flush; (3) soap, abrasive, water, scrub, and flush; (4) commercial powdered detergent (10% solution), tap water, scrub and flush; (5) complexing agent (1% citric acid), scrub and flush; and (6) chelating agent (1% versene), scrub and flush.

Removal efficiencies of the aqueous methods, expressed as average cumulative fractions of the initially deposited soil that was removed after three successive washings reported by Friedman (1958) are given in Table D-6, and the corresponding estimates of the parameter γ_j used in our models are given in Table D-7. All methods removed most of the contamination in the first washing; running tap water with scrub removed the least amount, and removal by the other five aqueous methods was similar. Variability in the measurements was substantially greater in the second and third washings than in the first. This result may indicate that removal by mechanical scrubbing was the most important in the first washing, and that chemical interactions involving the different cleansers became important in subsequent washings, when residual contamination was increasingly difficult to remove.

There may be limitations in applying results of the study by Friedman (1958) to other exposure situations. Possible limitations include that: (1) removal efficiencies could be different if soil or skin was moist at the time of contamination, rather than dry; (2) study subjects presumably kept their forearms mostly still between the time of deposition and times of washing, which probably minimized the extent of inadvertent shake-off of larger soil particles, especially before the first washing, that might be expected during normal daily activities; and (3) deliberate efforts to remove contamination might have resulted in higher removal efficiencies than would normally occur while showering, especially in areas of the body that are difficult to reach. The last concern also is an issue with other studies discussed above. Given these limitations, removal efficiencies in most situations, especially situations where significant contamination of skin is not expected, could be lower than estimates reported by Friedman (1958).

D.2.2.6 *Data from Study by Fogh et al.*

Fogh et al. (1999) reported results of a study to estimate the efficiency of removal of contaminants from skin by hand washing. Study subjects were exposed to specially prepared airborne particles of diameter 0.5, 2.5, or 10 μm in two indoor office environments, where contamination of skin occurred by dry deposition. Removal efficiencies by a single hand washing were 0.06 and 0.19 for 0.5-μm particles and ranged from 0.29 to 0.48 for the larger particles, with estimates for 2.5-μm particles tending to be the highest. Since particle sizes in this study were substantially smaller than particle sizes in most fallout to which military participants were exposed, including exposures in resuspension scenarios, estimated removal efficiencies probably have limited relevance to estimation of the parameter γ in the first shower after contamination. However, if most larger fallout particles would be removed in the first shower, results of this study may be representative of removal efficiencies in a second shower.

Fogh et al. (1999) also studied the efficiency of various methods of sampling contaminants from skin. These studies used rat skin that was exposed in a small test chamber to airborne particles of diameter 2.5, 4.5, or 8 μm. Results of those studies do not appear to be useful in estimating removal efficiencies. Methods of sampling did not resemble normal washing or showering, and results were not presented in a form that would allow estimation of the parameter γ.

Table D-1. Mean fractions of PbO initially deposited on palms of hands that was removed in successive 30-s wipes (Boeniger 2006)

Type of wipe[a]	Contamination level[b]	Fraction of initial contamination removed			
		Wipe 1	Wipe 2	Wipe 3	Wipe 4
PW	Low	0.56	0.13	0.070	0.037
PW	High	0.58	0.10	0.041	0.024
WD	Low	0.63	0.078	0.032	0.019
WD	High	0.60	0.087	0.035	0.017
GW	Low	0.57	0.085	0.035	0.027
GW	High	0.52	0.11	0.047	0.032

[a] PW = Palintest wipes (Palintest USA, Erlanger, KY); WD = Wash'n Dry wipes (Colgate-Palmolive, New York); GW = Ghost Wipes (Environmental Express, Mount Pleasant, SC).

[b] Low = Loading of PbO about 200 µg; High = Loading of PbO about 3,000 µg. Contaminated area of palms was about 1,060 cm^2.

Table D-2. Mean fractions of PbO deposited on palms of hands at time of each wiping that was removed in successive wipes (γ) estimated from data in Table D-1[a]

Type of wipe[b]	Contamination level[c]	Fraction of contamination at time of each wiping removed (γ)			
		Wipe 1	Wipe 2	Wipe 3	Wipe 4
PW	Low	0.56	0.30	0.23	0.16
PW	High	0.58	0.24	0.13	0.087
WD	Low	0.63	0.21	0.11	0.072
WD	High	0.60	0.22	0.11	0.061
GW	Low	0.57	0.20	0.10	0.088
GW	High	0.52	0.24	0.13	0.10
	Average	**0.58**	**0.23**	**0.13**	**0.094**
	Minimum	**0.52**	**0.20**	**0.10**	**0.061**
	Maximum	**0.63**	**0.30**	**0.23**	**0.16**

[a] Parameter γ is used in models developed in Section 3.5 and is calculated as described in Appendix D.2.2.1.

[b] PW = Palintest wipes (Palintest USA, Erlanger, KY); WD = Wash'n Dry wipes (Colgate-Palmolive, New York); GW = Ghost Wipes (Environmental Express, Mount Pleasant, SC).

[c] Low = Loading of PbO about 200 µg; High = Loading of PbO about 3,000 µg. Contaminated area of palms was about 1,060 cm^2.

Table D-3. Measurements of radioactive contamination of 15 native Marshallese affected by fallout from Operation CASTLE, Shot BRAVO in March 1954[a]

Individual identifier	External exposure rate (mR h^{-1}) at body surface[b]			
	Before first shower	Second reading	Third reading	Fourth reading
11	200	30	12	10
12	200	25	20	10
13	80	70	45	40
15	80	30	20	10
18	200	80	40	30
27	240	30		15
30	200	60	35	20
38	100	30	10	
46	200	30	25	15
52	80	70	70	40
56	80	50	20	15
57	200	100	50	30
60	200	100	30	30
74	200	100	60	35
77	400	20	15	7

[a] Data obtained from Part 1, Table 5.1 of Sharp and Chapman (1957). Second, third and fourth readings were made after successive showers.

[b] Measurements were made on March 3, two days after detonation of Shot BRAVO on March 1.

Table D-4. Fractional reductions in measured exposure rates at time of each shower after three successive showers (γ) estimated from data in Table D-3[a]

Individual identifier	Fractional reduction of exposure rate at time of each shower (γ)		
	First shower	Second shower	Third shower
11	0.85	0.60	0.17
12	0.88	0.20	0.50
13	0.13	0.36	0.11
15	0.63	0.33	0.50
18	0.60	0.50	0.25
27	0.88	0.50	
30	0.70	0.42	0.43
38	0.70	0.67	
46	0.85	0.17	0.40
52	0.13	0.00	0.43
56	0.38	0.60	0.25
57	0.50	0.50	0.40
60	0.50	0.70	0.00
74	0.50	0.40	0.42
77	0.95	0.25	0.53

[a] Parameter γ is used in models developed in Section 3.5 and is calculated as described in Appendix D.2.2.1.

Table D-5. Measurements of radioactive contamination of 28 military personnel affected by fallout from Operation CASTLE, Shot BRAVO in March 1954[a]

Individual identifier	Number of showers or washings	Exposure rate ($mR\ h^{-1}$) at body surface[b]				
		Before first shower	After first shower	Third reading	Fourth reading	After last shower
401	11	90	5	5	5	5
402	10	6	6	5	5	5
403	8	5	5	5		5
404	10	250	10	10	10	10
405	7	5	5	5	5	4
406[c]	7	5	5			5
407[c]	7	5	5	5		3.5
408	7	5	5	5	5	4
409[c]	5	150	10	10	10	10
410	5	20	10	10	10	10
411[c]	5	25	10	10	10	10
412[c]	5	25	15	15	15	15
413[c]	5	45	15	15	15	15
414[c]	5	100	15	15	15	15
415[c]	5	15	10	10	10	10
416	5	5	5	5	5	5
417	5	25	15	15	15	15
418[c]	5	100	10	10	10	8
419	5	30	15	15	10	10
420[c]	5	15	10	8	8	8
421	5	10	5	5	5	5
422[c]	5	15	5	4.5	4	4
423	5	40	15	10	10	10
424[c]	5	15	5	5	5	5
425[c]	5	150	15	15	15	15
426	5	20	5	4.5	4.5	4.5
427	5	200	25	25	25	25
428	5	100	10	10	10	10

[a] Data obtained from Part 2, Table 5.1 of Sharp and Chapman (1957).
[b] Measurements were made on March 2, one day after detonation of Shot BRAVO on March 1.
[c] Individual reported showering at least once before evacuation to Kwajalein Atoll.

Table D-6. Mean cumulative fractions of initially deposited labeled soil on forearms of volunteers that was removed in successive washings[a]

Method of aqueous decontamination	Cumulative fraction of initial contamination removed		
	First washing	Second washing	Third washing
Running tap water, with scrub	0.825	0.910	0.938
Soap (stearate salt) and water, scrub and flush	0.958	0.986	0.993
Soap, abrasive, tap water, scrub and flush	0.989	0.999	
Commercial powdered detergent (10% solution), tap water, scrub and flush	0.993	100.0	
Complexing agent (1% citric acid solution), scrub and flush	0.972	0.985	0.989
Chelating agent (1% versene solution), scrub and flush	0.990	0.999	

[a] Data obtained from Fig. No. 9 of Friedman (1958) apply when no barrier crèam was used.

Table D-7. Mean fractions of labeled soil deposited on forearms at time of each washing that was removed in successive washings (γ) estimated from data in Table D-6[a]

Method of aqueous Decontamination	Fraction of contamination at time of each washing removed (γ)		
	First washing	Second washing	Third washing
Running tap water, with scrub	0.825	0.49	0.31
Soap (stearate salt) and water, scrub and flush	0.958	0.67	0.50
Soap, abrasive, tap water, scrub and flush	0.989	0.91	
Commercial powdered detergent (10% solution), tap water, scrub and flush	0.993	1.0	
Complexing agent (1% citric acid solution), scrub and flush	0.972	0.46	0.27
Chelating agent (1% versene solution), scrub and flush	0.990	0.90	
Average	**0.95**	**0.74**	**0.36**
Minimum	**0.83**	**0.46**	**0.27**
Maximum	**0.99**	**1.0**	**0.50**

[a] Parameter γ is used in models developed in Section 3.5 and is calculated as described in Appendix D.2.2.1.

D.3 References

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APPENDIX E

EXAMPLE CALCULATIONS OF DOSES TO SKIN FROM DERMAL CONTAMINATION

E.1. Dermal Contamination by Descending Fallout at NTS

This section presents example calculations of dose for a hypothetical situation involving deposition of radioactive material onto skin due to exposure to descending fallout at NTS. We assume that a calculation of dose to skin of the forearms and back of the hands is desired. This example is intentionally simplified by assuming exposure to ^{90}Sr only.

For these calculations, we assume that an individual was exposed to descending fallout that resulted in an activity concentration of ^{90}Sr on the ground surface of 1 μCi m^{-2}. The assumed activity concentration is typical of concentrations in areas near ground zeros of nuclear tests at NTS in 1990 (McArthur 1991). We assume that the uncertainty in this activity concentration can be represented by a lognormal probability distribution with a geometric mean (GM) of 1 μCi m^{-2} and geometric standard deviation (GSD) of 2.0; this probability distribution has a 90% credibility interval (CI) that ranges from about 0.5 to about 2 μCi m^{-2}.

The skin contamination factor, a_h, for forearms and hands estimated from the volcanic ash studies in Costa Rica is about 115 cm^2 (Section 4.1.2), and the average surface area (s) of forearms and hands in adults is 1963 cm^2. These estimates give an average interception and retention fraction $r = (a_h/s)$ for forearms and hands of about 0.06. When uncertainties in the skin contamination factor and surface area of forearms and hands are taken into account, the resulting interception and retention fraction can be represented by a lognormal probability distribution with a GM of 0.06 and GSD of 3.0 (Table 4-1).

We assume that descending fallout contained an unknown distribution of particle sizes; this assumption results in the highest uncertainties in parameters used to adjust the interception and retention fraction (r) obtained from the volcanic ash studies. On the basis of this assumption, the particle-size adjustment factor, PS_a, is represented by a uniform probability distribution from 0.4 to 1.6 (mean of 1.0), the enrichment of specific activity, EF, is represented by a log-uniform probability distribution from 1.0 to 4.0, and the activity-weight adjustment factor, AW, is represented by a log-triangular probability distribution with a minimum at 0.01, mode at 0.1, and maximum at 1.0 (Table 4-2).

The remaining adjustment to the interception and retention fraction (r) is the enhancement due to moisture, EM. By assuming that the amount of moisture on skin of an

exposed individual at NTS was less than the amount of moisture on skin of human subjects in the volcanic ash studies in Costa Rica, the parameter *EM* is represented by a uniform probability distribution between 0.5 and 1.0, which has a mean of 0.75 (Table 4-2).

The dose-rate factor (*DRF*) for ^{90}Sr that applies to skin on the forearms and back of the hands is calculated using eq. (4-4) (Section 4.6.1) and an assumption that the nominal depth of radiosensitive tissues in those regions is 8 mg cm^{-2}. The calculated dose-rate factor for ^{90}Sr at a depth of 7 mg cm^{-2} is 6.8 rem h^{-1} per μCi cm^{-2} (Kocher and Eckerman 1987). Uncertainties in the dose-rate factor at a depth of 7 mg cm^{-2} are described in Section 4.6.1.1. A small uncertainty of about 10% in the dose-rate factor calculated by Kocher and Eckerman (1987) is represented by a normal probability distribution with a 90% CI of (6.1, 7.5) rem h^{-1} per μCi cm^{-2}. A backscatter correction for ^{90}Sr, which accounts for the neglect of backscattering of emitted electrons in air in calculations by Kocher and Eckerman (1987), is represented by a triangular probability distribution with a minimum at 0.7, mode at 0.8, and 0.9. The assumed uncertainty in the backscatter correction for ^{90}Sr is less than the uncertainty represented by the probability distribution developed in Section 4.6.1.1, which applies to mixtures of radionuclides in fallout with different maximum energies of emitted electrons. Finally, shielding of emitted electrons by particles deposited on skin is assumed to result in a reduction in the dose-rate factor for ^{90}Sr represented by a triangular probability distribution with a minimum at 0.6, mode at 0.8, and maximum at 1.0. The assumed uncertainty in the shielding correction for ^{90}Sr also is somewhat less than the uncertainty represented by the probability distribution for a mixture of radionuclides in fallout developed in Section 4.6.1.1.

As indicated in eq. (4-4), the dose-rate factor for ^{90}Sr at a depth of 7 mg cm^{-2} and its uncertainty that account for backscattering in air and shielding by particles is adjusted using a skin-depth modification factor, *SDMF*, to give a dose-rate factor that applies at the nominal depth of radiosensitive tissues of skin on the forearms and back of the hands of 8 mg cm^{-2}. As described in Section 4.6.1.2.2, the uncertainty in *SDMF* due to the variability in the depth of radiosensitive tissues in regions of the body where the nominal depth is 8 mg cm^{-2} is represented by a triangular probability distribution with a minimum at 0.7, mode at 0.95, and maximum at 1.3. The other source of uncertainty in *SDMF* discussed in Section 4.6.1.2.2 applies only in estimating a dose-rate factor for mixtures of radionuclides in fallout and is not included.

The effect of inefficient showering on the dose to skin is included in all calculations. The fraction of the contamination that is removed in each shower by exfoliation of skin cells (β) on the forearms and back of the hands is assumed to be represented by the probability distribution for the upper limbs given in Table 4-5. Probability distributions of removal fractions by showering (γ_j) for normal and highly efficient showering in Table 4-5 were assumed in separate calculations, to illustrate the effect of different assumptions about the efficiency of showering in removing contamination. The time between a detonation and deposition of ^{90}Sr on skin (T_0) is assumed to be 2 hours, the time between deposition and the first shower (ΔT_{post}) is assumed to be 12 hours, and the time between successive showers after the first is assumed to be 24 hours. However, the dose to skin in these calculations does not depend on T_0, because only a single radionuclide is assumed to be present and the rate of decrease of its activity is constant in time.

Using eqs. (3-2) to (3-5) in Section 3.2 and eq. (3-32) in Section 3.5.2 with the probability distributions of parameter values described above, we obtained probability distributions of doses to skin of the forearms and back of the hands from exposure to ^{90}Sr in descending fallout at NTS given in Table E-1. These results include the dose before the time of the first shower at 12 hours after deposition, D_1, the dose after the first shower, D_{sh}, and the total dose, $D_N = D_1 + D_{sh}$, after 120 daily showers ($N = 120$). The mean dose after the first shower in these calculations exceeds the mean dose before the first shower by a factor of about six when normal efficiency of showering is assumed but by less than 20% when showering is assumed to be highly efficient. An assumption of highly efficient showering decreases the mean total dose by a factor of three compared with the mean total dose assuming normal showering.

Table E-1 also gives the probability distribution of the dose to skin from exposure to the assumed concentration of ^{90}Sr in fallout deposited on the ground surface. The dose-rate factor for ground-surface exposure (1.86×10^{-2} rem h^{-1} per μCi cm^{-2}) is obtained from Table III.3 of Eckerman and Ryman (1993), and the exposure time is assumed to be 12 hours. The dose from dermal contamination exceeds the dose from ground-surface exposure even if the first shower is assumed to remove all contamination. When mean doses are compared, the total dose from dermal contamination is higher than the total dose from ground-surface exposure by a factor of more than 40 when normal showering is assumed and about 13 when showering is assumed to be highly efficient.

Table E-1. Probabilistic estimates of electron doses to skin from dermal contamination by ^{90}Sr in descending fallout at NTS and comparison with dose from exposure to ^{90}Sr on ground surface[a]

	Uncertainty distribution of electron dose (mrem)			
	5th percentile	50th percentile	Mean	95th percentile
Normal showering				
Dose before first shower (D_1)	2.6×10^{-3}	4.2×10^{-2}	1.8×10^{-1}	7.2×10^{-1}
Dose after first shower (D_{sh})	7.0×10^{-3}	1.6×10^{-1}	1.0	3.5
Total dose ($D_N = D_1 + D_{sh}$)	1.1×10^{-2}	2.1×10^{-1}	1.2	4.3
Highly efficient showering				
Dose before first shower (D_1)	2.6×10^{-3}	4.2×10^{-2}	1.8×10^{-1}	7.2×10^{-1}
Dose after first shower (D_{sh})	0.0	3.3×10^{-2}	2.1×10^{-1}	7.4×10^{-1}
Total dose ($D_N = D_1 + D_{sh}$)	4.9×10^{-3}	8.5×10^{-2}	3.9×10^{-1}	1.4
Dose from ground-surface exposure				
	6.9×10^{-3}	2.2×10^{-2}	2.9×10^{-2}	7.2×10^{-2}

[a] Calculations are described in Appendix E.1.

E.2. Dermal Contamination by Descending Fallout in the Pacific

E.2.1 Introduction

This section presents an example dose reconstruction for a participant in Operation SANDSTONE in the Pacific who was exposed during Shots XRAY, YOKE, and ZEBRA while stationed at Kwajalein Atoll. The participant later developed skin cancer on his face and, thus, estimates of dose to skin of the face are of interest.

This exercise provides estimates of electron dose to skin of the face due to deposition of descending fallout on that part of the body. Doses to skin from exposure to photons and alpha particles emitted by radionuclides deposited on skin and exposure to photons and electrons emitted by radionuclides in fallout deposited on the ground surface are not estimated.

Probabilistic estimates of doses to skin are obtained using Monte Carlo methods of propagating uncertainties in the various parameters used in the calculations. Point estimates of doses also are obtained using deterministic (point) estimates of parameter values. Monte Carlo methods allow estimation of the entire range of possible doses, including the upper 95% credibility limit used in adjudicating claims for compensation for radiogenic diseases by military participants at atmospheric weapons tests. A sensitivity analysis is performed to identify parameter uncertainties that contribute the most to the uncertainty in estimated doses.

E.2.2 Methods

Fallout from the three shots at Operation SANDSTONE reached Kwajalein Atoll within a few days after each detonation. The highest measured exposure rates (I) from fallout deposited on ships were 7×10^{-5} R h^{-1} at 150 hours after Shot XRAY, 5×10^{-4} R h^{-1} at 42 hours after Shot YOKE, and 4×10^{-5} R h^{-1}) at 144 hours after Shot ZEBRA.[32]

It is assumed that the participant was outside on the main deck of a ship at Kwajalein Atoll for the entire period of deposition of fallout. The activity concentration of radionuclides that were deposited and retained on skin (μCi cm$^{-2}_{skin}$) is estimated as a fraction of the activity

[32] Personal communication from N. Barss, SAIC, July 2004.

concentration that was deposited on the ship deck (μCi $cm^{-2}{}_{ship}$); the latter concentration is derived from the measured exposure rates. Fallout is assumed to have occurred around the time the maximum exposure rate was measured. Doses to skin from dermal contamination by descending fallout are estimated for each shot and as a total dose from all three shots. All calculations included assumptions about the efficiency of showering.

For comparison purposes, a second scenario is included in which it is assumed that the participant was outdoors, on land, at Kwajalein Atoll. The difference between the two scenarios is that the area of surface contamination on a ship is finite, whereas the atoll is sufficiently large that it essentially represents an infinite contaminated area. This difference affects the calculated activity concentration of radionuclides in deposited fallout corresponding to a known exposure rate and the uncertainty in the calculated concentration.

The electron dose to skin of the face (rem) from dermal contamination by descending fallout has two components: (1) the dose from the time of deposition of radionuclides on skin until the time of the first shower, denoted by D_1, and (2) the dose after the first shower that results from incomplete removal of contamination by showering, denoted by D_{sh}. In accordance with eq. (3-6) in Section 3.2.2 and eq. (3-35) in Section 3.5.2, the two components of the total dose are calculated as:

$$
\begin{aligned}
D_1 &= \left[A_0 \cdot \int_{t_{\max}}^{t_{\max}+\Delta T_{post}} t^{-x}\, \mathrm{d}t \right] \cdot AR_f \cdot DRF_{4\,mg\,cm^{-2}} \\
&= \left[A_0 \frac{t_{\max}^{-x+1} - \left(t_{\max} + \Delta T_{post}\right)^{-x+1}}{(x-1)} \right] \cdot AR_f \cdot DRF_{4\,mg\,cm^{-2}}
\end{aligned}
\tag{E-1}
$$

$$
D_{sh} = A_0 \cdot AR_f \cdot DRF_{4\,mg\,cm^{-2}} \cdot \sum_{j=2}^{N} \left[\frac{T_{j-1}^{-(x-1)} - T_j^{-(x-1)}}{x-1} \cdot \left(\prod_{k=1}^{j-1} \alpha_k \right) \right]
\tag{E-2}
$$

where

A_0 = reference activity concentration of radionuclides on ship or ground surface at 1 hour after detonation (μCi $cm^{-2}{}_{ground}$) – see eq. (E-3);

t_{max} = time after detonation when maximum exposure rate due to fallout on ship was measured and deposition on skin occurred (h);

ΔT_{post} = period between acute fallout event and time of first shower (h);

x = shot-specific exponent that accounts for effect of radioactive decay on time-dependence of external exposure rate (unitless);

AR_f = fraction of activity concentration of radionuclides deposited on ship or ground surface that is intercepted and retained on skin (unitless) –see eq. (E-4);

$DRF_{4\ mg\ cm^{-2}}$ = electron dose rate per unit activity concentration of radionuclides deposited on skin (rem h^{-1} per μCi cm^{-2}) at nominal depth below body surface of 4 mg cm^{-2};

T_j = time after detonation of j^{th} shower (h), where $T_1 = t_{\text{max}} + \Delta T_{post}$; and

α_j = $1 - (\gamma_j + \beta)$ (unitless), where γ_j is fraction of activity of radionuclides on skin that is removed by washing during the j^{th} shower and β is fraction of activity that is removed by exfoliation of skin cells during each shower and between successive showers.

The total dose to skin after N showers is $D_N = D_1 + D_{sh}$. In this exercise, N is assumed to be 120 days, meaning that the additional dose after 120 daily showers, which occur at a regular interval of 24 hours, is assumed to be negligible.

The reference activity concentration, A_0, is estimated by applying a decay correction to the activity concentration on a ship or ground surface at the time the highest exposure rate was measured:

$$A_0 = A_{\text{max}}\left(t_{\text{max}}^{+x}\right) \tag{E-3}$$

where

A_{max} = activity concentration of radionuclides on ship or ground surface at time t_{max} (μCi cm$^{-2}{}_{\text{ground}}$) – see eq. (E-4).

The maximum activity concentration (A_{max}) on a ship or the ground surface is estimated using the highest measured exposure rate (I) at time t_{max} after a detonation and a pre-calculated gamma constant (Γ), which is obtained as described by Egbert et al. (1985):

$$A_{\max} = \frac{(I / k_m)}{\Gamma \cdot k_f \cdot k_r} \tag{E-4}$$

where

I = maximum exposure rate (R h^{-1}) at time $t_{\max}$ after detonation;

k_m = bias correction factor (unitless) to account for tendency of instrument readings to overestimate actual exposure rate;

Γ = calculated exposure rate at height of 1 m per unit activity concentration of radionuclides in fallout distributed uniformly on infinite plane surface at time $t_{\max}$ after detonation (R h^{-1} per μCi cm^{-2});

k_f = bias correction factor (unitless) that applies when contaminated surface of ship or ground is finite; and

k_r = bias correction factor (unitless) to account for shielding provided by roughness of ship or ground surfaces.

A fraction AR_f of the activity of descending fallout is intercepted and retained on skin of the face of the exposed individual. As described in Section 3.2, this fraction is estimated as:

$$AR_f = r \cdot PS_a \cdot EM \cdot EF \cdot AW \tag{E-5}$$

where

r = interception and retention fraction for skin of face (unitless) estimated from studies of deposition and retention of volcanic ash particles;

PS_a = adjustment factor (unitless) that represents how retention on skin depends on particle size of material incident on body surface and accounts for difference between weight particle-size distribution of fallout at location of interest and particle-size distribution for which interception and retention fraction (r) was estimated using data from volcanic ash studies;

EM = adjustment factor (unitless) that accounts for dependence of efficiency of retention of deposited particles on amount of moisture on skin;

EF = specific-activity enrichment factor (μCi g^{-1}_{skin} per μCi $g^{-1}_{surface}$) that accounts for experimental evidence indicating that specific activity of soil retained on skin is higher than specific activity of soil on ground when radionuclides are preferentially distributed on particle surfaces;

AW = activity-weight adjustment factor (unitless) that accounts for difference between activity and weight particle-size distributions in fallout at location of interest.

The dose to radiosensitive tissues of skin on the face is estimated using a dose-rate factor (*DRF*) that applies at the nominal depth of radiosensitive tissues in that region of the body surface:

$$DRF_{4\,mg\,cm^{-2}} = DRF_{7\,mg\,cm^{-2}} \cdot SDMF \qquad \text{(E-6)}$$

where

$DRF_{7\,mg\,cm^{-2}}$ = dose rate per unit activity concentration of all radionuclides combined on skin (rem h^{-1} per μCi cm^{-2}) at depth of 7 mg cm^{-2}, which is a standard depth used in estimating electron doses to skin; and

SDMF = skin-depth modification factor (unitless) that accounts for assumption that radiosensitive tissues of skin on face are located at average depth of 4 mg cm^{-2}.

E.2.3 Description of Parameters and Assumed Probability Distributions

The following sections describe the various parameters in the model equations and assumptions about probability distributions to represent their uncertainty.

E.2.3.1 *Measured Exposure Rate* (*I*)

The contaminated plume from each of the nuclear detonations of concern arrived at Kwajalein Atoll within a few days after the tests. The exposure rate from radioactive material that accumulated on a ship or on the ground surface increased and reached a maximum as the plume passed by the atoll. The maximum exposure rate is used in this exercise to estimate the activity concentration of radionuclides on a ship or ground surface. The highest measured

exposure rates (I) and times when those readings were taken ($t_{\max}$) noted in Appendix E.2.2 are given in Table E-2. It is assumed that the measurements were taken in the same place where the exposed individual was located.

An uncertainty of a factor of two is assigned to the maximum exposure rate (I) to account for the variability in instrument readings of about ± 30% (NRC 1985; Table C-6) and possible errors in reading an instrument (e.g., calibration errors, inappropriate height above ground, misreading of instrument). This uncertainty is represented by a log-uniform probability distribution with a minimum at $I/2$ and maximum at $I \times 2$.

E.2.3.2 *Bias in Instrument Reading* (k_m)

Documentation of survey instruments used during the weapons testing program indicates that they could have overestimated the true exposure rate by about 40% (NRC 1985). Thus, on average, the bias correction factor (k_m) is assumed to be 1.4. A small uncertainty represented by a triangular probability distribution with a minimum at 1.3, mode at 1.4, and maximum at 1.5 is assigned to this factor.

E.2.3.3 *Gamma Constant* (Γ)

The gamma constant (Γ) gives the exposure rate per unit activity concentration of all radionuclides in fallout on the ground surface combined and is calculated by assuming an infinite plane source and no fractionation of radionuclides. Deterministic (point) estimates of the gamma constant at the time of maximum exposure rate, $t_{\max}$, at each test were obtained from the FIIDOS computer code (Egbert et al. 1985) and are given in Table E-2.

An uncertainty of a factor of two is assigned to each gamma constant to account for uncertainties in the fission mode, the degree of fractionation in fallout, and calculations of photon transport in air. This uncertainty is represented by a log-uniform probability distribution with a minimum at $\Gamma/2$ and maximum at $\Gamma \times 2$.

E.2.3.4 *Bias to Account for Finite Area of Contaminated Surface* (k_f)

The reported gamma constant was calculated by assuming that the source region is an infinite plane. For a finite surface, such as the deck of a ship, the gamma constant is lower by a factor k_f. Equivalently, if the same exposure rate is measured above an infinite and a finite surface, the activity concentration of radionuclides on the infinite surface is lower by a factor k_f.

Bias factors to account for finite sources have been estimated for different rectangular and circular surfaces (Apostoaei et al. 2000). If we assume that the width of ships can range from 10 to 50 m (30 to 160 feet), as indicated by data summarized in Table E-3, k_f can vary between 0.2 and 0.8. On the basis of this assumption, a uniform probability distribution between 0.2 and 0.8 is assigned to this parameter. No bias correction to account for finite source regions is needed when exposure occurred on land.

E.2.3.5 *Bias to Account for Surface Roughness* (k_r)

The gamma constant (Γ) is calculated by assuming that a contaminated surface is a perfectly smooth plane. However, real surfaces have many irregularities and inherent roughness. The gamma constant for a rough surface is lower by a factor k_r when the shielding provided by roughness is taken into account.

Burson and Profio (1977) provide reduction factors (k_r) for different surfaces including paved areas, lawns, graveled areas, and plowed fields. Surfaces on a ship are relatively smooth, probably similar to paved surfaces or even smoother. A reasonable range of values of k_r on a ship is 0.8 to 1.0. However, land surfaces are more uneven, and k_r may vary from 0.5 to 0.9 (Burson and Profio 1977). Uniform probability distributions between these limits are assigned to this parameter in cases of exposure on ship or land.

E.2.3.6 *Radioactive Decay Exponent* (x)

The activity of all radionuclides in fallout combined decreases with time as t^{-x}. Estimates of the exponent x are 0.545 at Shots XRAY and YOKE and 1.1 at Shot ZEBRA.[33] The uncertainty in x is assumed to be represented by a normal probability distribution with the mean specified above and a standard deviation of 0.1 (NRC 2003; page 151).

E.2.3.7 *Time from Deposition on Skin Until First Shower* (ΔT_{post}); *Time Between Showers*

Accumulation of radionuclides on skin during a fallout episode presumably occurred continuously during passage of the plume, which normally took a few hours. Consequently, it probably is reasonable to assume that contamination was present on skin for at least 6 hours. Given the hot climate in the Marshall Islands, participants presumably showered at least once each day. Thus, it is reasonable to assume that participants showered within 24 hours after passage of the plume. Since the time from deposition on skin until the first shower is unknown, a uniform probability distribution between 6 and 24 hours is assumed for this parameter.

As noted previously, the time between successive showers after the first ($T_j - T_{j-1}$, $j \geq 2$) is assumed to be 24 hours, with no uncertainty.

E.2.3.8 *Interception and Retention Fraction* (r)

The interception and retention fraction (r) discussed in Section 4.1 is estimated on the basis of data on deposition and retention of volcanic ash on human subjects in Costa Rica (Miller 1966a,b). The uncertain interception and retention fraction, r, for skin of the face is represented by a lognormal probability distribution with a GM of 0.015 and GSD of 3.6 [90% CI of (0.002, 0.12); Table 4-1].

The interception and retention fraction, r, is calculated as (a_h/s_f), where a_h (cm^2) is a skin contamination factor that is estimated from data obtained in the volcanic ash studies as the weight of particles deposited and retained on skin of the face divided by the weight of particles

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[33] Personal communication from N. Barss, SAIC, July 2004.

deposited per unit area on the ground surface, and s_f is the surface area of the face (cm^2). The uncertainty in the interception and retention fraction for the face is determined almost entirely by the assumed uncertainty in a_h (Section 4.1.3).

E.2.3.9 *Particle-Size Adjustment* (PS_a)

Particle-size distributions of volcanic ash in the studies of deposition and retention on skin in Costa Rica had a median diameter of about 80 μm, and some particles were as large as 300 μm (Miller 1966a; page 324). However, given that tests at Operation SANDSTONE took place sufficiently far from Kwajalein Atoll that the plumes reached the atoll only after two or more days, the particle-size distribution in fallout at Kwajalein can be assumed to have had a median diameter of 50 μm or less. Since smaller particles are more efficiently retained on skin than larger particles, it is expected that retention on skin was enhanced in this case by a factor PS_a that can be represented by lognormal probability distribution with a GM of 1.3 and GSD of 1.1 (Section 4.2.1.1, Table 4-2).

E.2.3.10 *Enhancement of Retention Due to Moisture on Skin* (*EM*)

It is reasonable to assume that participants in the Pacific had considerable amounts of moisture on their skin due to the warm and humid conditions. Since the volcanic ash studies in Costa Rica took place under similar conditions, we assume that the enhancement of retention on skin due to the presence of moisture (*EM*) on skin in the Pacific is represented by a uniform probability distribution between 0.8 and 1.5 (Section 4.2.2, Table 4-2).

E.2.3.11 *Enrichment of Specific Activity* (*EF*)

Most fallout particles at Kwajalein Atoll from shots at Operation SANDSTONE presumably were small (mostly less than 100 μm, with median diameters less than 50 μm), and some radionuclides in fallout (mainly refractory elements) presumably were distributed in the volume of fallout particles, rather than on particle surfaces, as a result of fractionation. Thus, at Kwajalein Atoll, it is expected that little or no enrichment in specific activity occurred, and

minimal values of the parameter *EF* are assumed. The uncertainty in this parameter is represented by a triangular probability distribution with a minimum and mode at 1.0 and maximum at 2.0 (Section 4.2.3, Table 4-2).

E.2.3.12 *Activity-Weight Adjustment Factor* (*AW*)

At NTS, the activity particle-size distribution in fallout at locations close to ground zero was found to differ from the weight particle-size distribution (e.g., see Figs. 8 to 15 of Miller 1969). For example, in a sample of fallout from Shot SHASTA, particles of diameter less than 100 μm comprised 24% of the weight, but those particles carried only 0.75% of the activity. Since most particles that can stick to skin have diameters less than 100 μm, the activity concentration of fallout particles retained on skin relative to the activity concentration of fallout deposited on the ground surface would be smaller at NTS than indicated by values of the skin contamination factor (a_h) that were derived from the volcanic ash studies in Costa Rica.

However, fallout reaching Kwajalein Atoll presumably contained mostly small particles (< 100 μm, with median particle diameters < 50 μm). Thus, in contrast to exposures to fallout at NTS, little or no additional adjustment to account for differences between activity and weight particle-size distributions is needed in assessing dermal contamination at Kwajalein Atoll. In this exercise, the parameter *AW* is represented by a triangular probability distribution with a minimum at 0.7 and a mode and maximum at 1.0 (Section 4.2.4, Table 4-2).

E.2.3.13 *Dose-Rate Factor* (*DRF*) *at Depth of 7 mg cm*$^{-2}$

Dose-rate factors (*DRF*s), which give dose rates to radiosensitive tissues in the basal layer of skin per unit activity concentration of beta-emitting radionuclides on the body surface, are discussed in Section 4.6.1. For mixtures of radionuclides in fallout, a nominal dose-rate factor that applies at a depth below the body surface of 7 mg cm^{-2} (70 μm) in units of rem h^{-1} per μCi cm$^{-2}_{skin}$ can be represented by a triangular probability distribution with a minimum at 1.6, mode at 3.7, and maximum at 6.8 (Table 4-2). This probability distribution accounts for uncertainties in the nominal dose-rate factor due to uncertainties in calculations of electron transport, shielding of electrons by fallout particles, and a backscatter correction.

E.2.3.14 *Skin-Depth Modification Factor* (*SDMF*)

The skin-depth modification factor (*SDMF*) takes into account that the dose-rate factor (*DRF*) described in the previous section is estimated at a depth below the body surface of 7 mg cm^{-2}, whereas radiosensitive tissues in skin of the face are located at an average depth of about 4 mg cm^{-2} (Whitton 1973). The depth of radiosensitive tissues on the face can vary from 20 to 100 μm (ICRP 1975; Charles 1986). An uncertainty in the skin-depth modification factor for the face that takes into account the variability in the depth of radiosensitive tissues and the effect of mixtures of radionuclides in fallout is discussed in Section 4.6.1.2.1. The uncertainty in this parameter is represented by a triangular probability distribution with a minimum at 0.7, mode at 1.3, and maximum at 1.7 (Table 4-2).

E.2.3.15 *Removal Fractions of Contamination from Skin* (γ_j, β)

In addition to the effect of radioactive decay, the activity concentration of radionuclides on skin is assumed to be reduced over time by showering and exfoliation of skin cells. The removal fraction by showering (γ_j) is assumed to be highest in the first shower, to decrease in the next three showers, and to remain constant in all showers after the fourth, whereas the removal fraction by exfoliation, which also accounts for removal of skin cells between showers, is assumed to be the same in all showers (Sections 4.7.1 and 4.7.2, Table 4-5).

The example calculations in this appendix are concerned with estimating dose to skin of the face. Given that most participants shaved, as well as showered, on a daily basis, the removal fraction by exfoliation of skin cells (β) should be higher than values that apply in most other parts of the body. In this exercise, we assume that the highest value of β in Table 4-5 (the value for upper limbs) applies to the face. In addition, by assuming that personnel who were exposed to fallout at Operation SANDSTONE were aware of their exposures as they occurred, removal fractions by showering (γ_j) that apply when showering is highly efficient in removing contamination are assumed to be appropriate. The selected values of these parameters are given in Table E-2.

E.2.4 Estimated Doses to Skin at Kwajalein Atoll

Doses to skin from dermal contamination by descending fallout at Shots XRAY, YOKE and ZEBRA in Operation SANDSTONE were estimated for a participant on a ship stationed at Kwajalein Atoll. As an alternative scenario, doses to skin also were estimated for a participant on land at Kwajalein Atoll.

A summary of parameter values used in this exercise is given in Table E-2. For each parameter, a probability distribution that is assumed to represent its uncertainty is given. This table also provides a deterministic (point) estimate of each parameter, which was chosen to be the mean of a normal or uniform distribution, the geometric mean of a lognormal or log-uniform distribution, or the mode of a triangular distribution.

Probability distributions of doses to skin from dermal contamination were estimated using Monte Carlo methods of uncertainty propagation. Point estimates of doses also were obtained using deterministic parameter values. As indicated in results described below, a deterministic estimate of dose is substantially less than the corresponding mean of a probability distribution when the uncertainty in an estimated dose is large.

Deterministic and probabilistic estimates of electron doses to skin obtained by assuming that a participant was stationed on a ship near Kwajalein Atoll are presented in Table E-4. The probability distribution of the dose to the time of the first shower from all three shots combined has a 50th percentile at 0.039 rem, mean at 0.10 rem, and 95th percentile at 0.41 rem; an uncertainty factor, defined as the ratio of the 95th and 50th percentiles, is 11, and the ratio of the 95th and 5th percentiles is 85. The dose after the first shower has a 50th percentile at 0.015 rem, mean at 0.050 rem, and 95th percentile at 0.2 rem (uncertainty factor of 13). The total dose has a 50th percentile at 0.058 rem, mean at 0.15 rem, and 95th percentile at 0.59 rem (uncertainty factor of 10). About two-thirds of the total dose is received before the first shower.

The most important contributors to the uncertainty in estimated doses to skin for a participant on a ship were identified by performing a sensitivity analysis, which provides percent contributions of the variance of each parameter to the variance in the total dose. Results of a sensitivity analysis for exposure to fallout at Shot YOKE, which delivered the largest dose, are given in Table E-5. The largest contributor to the uncertainty in all three doses is the uncertainty

in the interception and retention fraction (r). As noted previously, the uncertainty in r is due almost entirely to the uncertainty in the skin contamination factor (a_h). The second largest contributor to the uncertainty in the dose after the first shower is the uncertainty in the removal fractions by showering (γ_j).[34] However, the uncertainty in the efficiency of showering is not an important contributor to the uncertainty in the total dose.

The uncertainty in the dose to skin for a participant stationed on a ship could be reduced if the type of ship is specified. In such cases, a narrower probability distribution of the bias factor to account for the finite size of a ship (k_f) could be used. However, since this parameter is not an important source of uncertainty in estimated doses to skin, any adjustments of the probability distribution for k_f would have little impact on uncertainties in estimated doses.

Doses to skin for a participant exposed on land at Kwajalein Atoll given in Table E-6 are about 60% of the doses on a ship given in Table E-4. This reduction is mostly a consequence of the effect of the finite surface area of the ship (i.e., increase in the concentration of radionuclides in deposited fallout corresponding to a given exposure rate). Although the effect of the finite area of a ship is a reduction in dose by a factor of two, on average, this effect is partly offset by the greater shielding on land due to ground roughness.

In the analysis of doses due to exposure on land, the sensitivity analysis for exposures at Shot YOKE summarized in Table E-7 indicates that the main sources of uncertainty are similar to those for exposure on a ship, with one exception. As indicated in Table E-5, the uncertainty in the finite surface area bias (k_f) has some importance in cases of exposure on a ship, but this parameter is not used in estimating dose on land.

[34] Only the removal fraction in the first shower, γ_1, is assumed to be uncertain. This assumption is appropriate when all uncertain values of γ_j are assumed to be perfectly correlated and parameter sensitivity is calculated in Crystal Ball® by computing rank correlation coefficients between every assumption and the model output (Decisioneering 2001).

Table E-2. Summary of parameter values used in estimating electron doses to skin of face from dermal contamination by descending fallout

Parameter	Symbol	Unit	Deterministic value	Uncertainty distribution[a]
Peak exposure rate	I	R h^{-1}		
Shot XRAY			7×10^{-5} [b]	LU (I/2, I×2)
Shot YOKE			5×10^{-4} [b]	LU (I/2, I×2)
Shot ZEBRA			4×10^{-5} [b]	LU (I/2, I×2)
Time of maximum exposure rate after detonation	t_{max}	h		
Shot XRAY			150[b]	Constant
Shot YOKE			42[b]	Constant
Shot ZEBRA			144[b]	Constant
Instrument reading bias	k_m	unitless	1.4	T (1.3, 1.4, 1.5)
Gamma constant	Γ	R h^{-1} per μCi cm^{-2}		
Shot XRAY			0.0545	LU (Γ/2, Γ×2)
Shot YOKE			0.0540	LU (Γ/2, Γ×2)
Shot ZEBRA			0.0574	LU (Γ/2, Γ×2)
Finite surface area bias	k_f	unitless		
On ship			0.5	U (0.2, 0.8)
On land			1.0	Constant
Surface roughness bias	k_r	unitless		
On ship			0.9	U (0.8, 1.0)
On land			0.7	U (0.5, 0.9)
Radioactive decay exponent	x	unitless		
Shot XRAY			0.545	N (0.545, 0.1)
Shot YOKE			0.545	N (0.545, 0.1)
Shot ZEBRA			1.1	N (1.1, 0.1)
Time between contamination of skin and first shower	ΔT_{post}	h	15	U (6, 24)
Interception and retention fraction for face	r	unitless	0.015	LN (0.015, 3.6)
Particle-size adjustment	PS_a	unitless	1.3	LN (1.3, 1.1)
Enhancement due to moisture	EM	unitless	1.15	U (0.8, 1.5)
Enrichment of specific activity	EF	unitless	1	T(1.0, 1.0, 2.0)
Activity-weight adjustment	AW	unitless	1	T(0.7 ,1.0, 1.0)

Table is continued on following page.

Table E-2. Summary of parameter values used in estimating electron doses to skin of face from dermal contamination by descending fallout (continued)

Parameter	Symbol	Unit	Deterministic value	Uncertainty distribution[a]
Dose rate factor at 7 mg cm^{-2}	*DRF*	rem h^{-1} per $\mu Ci\ cm^{-2}$	3.7	T (1.6, 3.7, 6.8)
Skin depth modification factor	*SDMF*	unitless	1.3	T (0.7, 1.3, 1.7)
Fraction removed by washing per shower	γ	unitless		
1st shower	γ_1		0.85	T (0.7, 0.85, 1.0)
2nd shower	γ_2		0.60	T (0.4, 0.6, 0.8)
3rd shower	γ_3		0.25	T (0.1, 0.25, 0.4)
≥ 4th shower	γ_{4+}		0.02	T (0.005, 0.02, 0.035)
Fraction removed by exfoliation of skin cells per shower[c]	β	unitless	0.05	T (0.025, 0.05, 0.07)

[a] LU = Log-uniform (minimum, maximum); T = Triangular (minimum, mode, maximum); U = Uniform (minimum, maximum); N = Normal (mean, standard deviation); LN = Lognormal (median, geometric standard deviation).

[b] Point estimate based on measurements after each shot.

[c] Removal fraction for skin on upper limbs is assumed to apply to face.

Table E-3. Dimensions of typical ships of U.S. Navy (1940–1945)[a]

Type of ship[b]	Length (ft)	Width (ft)
Light aircraft carrier		
Independence Class (USS Independence)	622	109
Escort carrier		
USS Bairoko CVE-115 (Commencement Bay class)	557	105
Battleships		
South Dakota class	680	108
Iowa class	888	108
Light Cruiser		
Atlanta class	542	53
Amphibious force command ships		
Mount McKinley Class (e.g., Estes AGC-12)	459	63
Landing craft		
Landing Craft Infantry (Gunboat) – LCI(G)	160	23
Ocean fleet tugboats		
ATF (e.g., COCOPA, MOLALA, TAWAKONI)	205	39
Yard ships (YAG)		
Yard ships (YAG)	450	70
Liberty type yard ship (YAG 39/YAG 40)	441	56
Barges	70	35

[a] Source: Personal communication from N. Barss, SAIC, August 24, 2004; see also "Ships of the U.S. Navy, 1940-1945," available at http://www.ibiblio.org/hyperwar/USN/USN-ships.html.

[b] List of typical vessels of the U.S. Navy. Not all such ships participated at Pacific nuclear weapons tests.

Table E-4. Deterministic and probabilistic estimates of electron doses to skin from dermal contamination by descending fallout for participants on ship stationed at Kwajalein Atoll during Operation SANDSTONE

	Electron dose to skin of face (rem)				
	Deterministic estimate	Uncertainty distribution			
		5th percentile	50th percentile	Mean	95th percentile
			Dose to time of first shower (D_1)		
Shot XRAY	0.0032	0.00027	0.0036	0.014	0.050
Shot YOKE	0.022	0.0020	0.025	0.083	0.37
Shot ZEBRA	0.0017	0.00015	0.0019	0.0067	0.027
TOTAL	**0.027**	**0.0049**	**0.039**	**0.10**	**0.41**
Uncertainty factor					
95th/50th			11		
95th/5th			85		
			Dose after first shower (D_{sh})		
Shot XRAY	0.0017	0.0	0.0016	0.0087	0.032
Shot YOKE	0.0083	0.0	0.0088	0.038	0.16
Shot ZEBRA	0.00063	0.0	0.00068	0.0028	0.012
TOTAL	**0.011**	**0.0**	**0.015**	**0.050**	**0.20**
Uncertainty factor					
95th/50th			13		
95th/5th			Not defined		
			Total dose ($D_N = D_1 + D_{sh}$)		
Shot XRAY	0.0049	0.0005	0.0059	0.022	0.083
Shot YOKE	0.030	0.0028	0.0370	0.12	0.52
Shot ZEBRA	0.0023	0.00021	0.0028	0.0095	0.038
TOTAL	**0.037**	**0.0073**	**0.058**	**0.15**	**0.59**
Uncertainty factor					
95th/50th			10		
95th/5th			80		

Table E-5. Sensitivity analysis of probabilistic estimates of electron doses to skin of the face from dermal contamination by descending fallout from Shot YOKE for participants on ship stationed at Kwajalein Atoll during Operation SANDSTONE

Parameter	Contribution to uncertainty		
	Dose to time of first shower (D_1)	Dose after first shower (D_{sh})	Total dose ($D_N = D_1 + D_{sh}$)
I	4.7%	3.2%	4.7%
k_m	0.038%	0.019%	0.016%
Γ	5.2%	4.4%	5.5%
k_f	7.1%	4.5%	6.8%
k_r	0.27%	0.21%	0.29%
x	0.016%	0.44%	0.018%
ΔT_{post}	6.4%	0.0017%	3.2%
r	66%	45%	67%
PS_a	0.39%	0.43%	0.45%
EM	1.8%	1.1%	1.7%
EF	1.5%	1.0%	1.5%
AW	0.75%	0.18%	0.57%
γ_j		35%	3.0%
β		1.3%	0.066%
$DRF_{7\ mg\ cm^{-2}}$	4.1%	2.2%	3.9%
$SDMF$	1.6%	0.84%	1.5%

Table E-6. Deterministic and probabilistic estimates of electron doses to skin from dermal contamination by descending fallout for participants on land at Kwajalein Atoll during Operation SANDSTONE

	Electron dose to skin of face (rem)				
	Deterministic estimate	Uncertainty distribution			
		5th percentile	50th percentile	Mean	95th percentile
			Dose to time of first shower (D_1)		
Shot XRAY	0.0021	0.00017	0.0022	0.0077	0.028
Shot YOKE	0.014	0.0012	0.015	0.047	0.19
Shot ZEBRA	0.0011	0.00011	0.0012	0.0039	0.015
TOTAL	**0.017**	**0.0033**	**0.024**	**0.058**	**0.22**
Uncertainty factor					
95th/50th			9		
95th/5th			67		
			Dose after first shower (D_{sh})		
Shot XRAY	0.0011	0.0	0.0010	0.0048	0.019
Shot YOKE	0.0053	0.0	0.0053	0.021	0.088
Shot ZEBRA	0.00041	0.0	0.00039	0.0016	0.0070
TOTAL	**0.0068**	**0.0**	**0.09**	**0.028**	**0.11**
Uncertainty factor					
95th/50th			12		
95th/5th			Not defined		
			Total dose ($D_N = D_1 + D_{sh}$)		
Shot XRAY	0.0031	0.00029	0.0035	0.013	0.048
Shot YOKE	0.019	0.0018	0.023	0.068	0.27
Shot ZEBRA	0.0015	0.00016	0.0017	0.0054	0.021
TOTAL	**0.024**	**0.0048**	**0.035**	**0.086**	**0.31**
Uncertainty factor					
95th/50th			9		
95th/5th			65		

Table E-7. Sensitivity analysis of probabilistic estimates of electron doses to skin of the face from dermal contamination by descending fallout from Shot YOKE for participants on land at Kwajalein Atoll during Operation SANDSTONE

Parameter	Contribution to uncertainty		
	Dose to time of first shower (D_1)	Dose after first shower (D_{sh})	Total dose ($D_N = D_1 + D_{sh}$)
I	5.1%	3.5%	5.1%
k_m	0.049%	0.014%	0.025%
Γ	5.7%	4.8%	5.9%
k_f	N/A	N/A	N/A
k_r	1.0%	0.82%	1.0%
x	0.010%	0.46%	0.027%
ΔT_{post}	6.6%	0.0001%	3.2%
r	71%	46%	71%
PS_a	0.37%	0.40%	0.43%
EM	1.9%	1.1%	1.9%
EF	1.2%	0.87%	1.2%
AW	0.77%	0.17%	0.58%
γ_j		37%	3.5%
β		1.3%	0.051%
$DRF_{7\ mg\ cm^2}$	4.7%	2.4%	4.5%
$SDMF$	1.9%	1.0%	1.8

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ATTN: Ms. Nancy Daugherty, CHP

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McLean, VA 22102
ATTN: Dr. Mondher Chehata

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102 Donner Drive
Oak Ridge, TN 37830
ATTN: Dr. David C. Kocher